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Program VSMOKE— Users Manual

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Contents

Abstract

This is a users manual for VSMOKE, a computer **program** for predicting **the** smoke and dry **weather** visibility impact of a single prescribed fire at several downwind locations. VSMOKE is a **FORTRAN** 77 program that depends on the input in **file VSMOKE.IPT** to generate output in **file VSMOKE.OUT. VSMOKE** is based on steady-state Gaussian plume modeling principles compatible with those used by the U.S. Environmental Protection Agency. VSMOKE is uniquely tailored as a plume model for a low to moderate intensity ground **fire** as an emissions source.

Keywords: Computer models, prescribed **fire,** smoke, visibility, **VSMOKE.**

Introduction

Fog, smoke from forest burning, or a combination of both can reduce visibility. Low visibility can increase the hazards of road travel. Land managers must be able to assess the risk of a prescribed fire reducing visibility and increasing driving hazards. Two numerical indexes, the Dispersion Index (Lavdas 1986) and the **Low** Visibility Occurrence Risk Index (Lavdas and **Hauck** 199 1) were developed to help managers make this assessment.

These indexes represent only part of VSMOKE, a FORTRAN 77 computer program designed as an atmospheric dispersion model that estimates the effects of a prescribed forestry burn on air quality and visibility. Also useful for evaluating similar emission sources, such as agricultural burns and **wildfires,** this dispersion model is a modularly designed algorithm, from both an internal and external perspective. Components within **VSMOKE** are relatively easy to isolate, and the program can become a component within a more extensive family of programs. For example, **VSMOKE** fits into a family of programs when input data are derived from the results of computerized **fire** and emissions models and output data are used in post-processor programs, such as graphical display systems.

VSMOKE will help those responsible for forestry-prescribed burning assess the hazards associated with smoke, especially roadway hazards. As a "stand alone" program, VSMOKE and this manual are designed to be used primarily by air quality specialists with background in atmospheric dispersion modeling. This user group will be particularly interested in the technical development and overall performance of the model. Although the FORTRAN list-directed input format should present minimal difficulty for these users, even the most experienced should review the input/output sections, paying close attention to unique input and output features.

The structure and format of VSMOKE! and its associated input/output files allow for development of pre- and post-processor programs to interface with other users, including those directly responsible for prescribed forest **fires.** A few sections in this manual are designed to help computer programmers and systems analysts develop these interfaces. As these specialists become more familiar with VSMOKE, they will be able to provide fue managers with information pertinent to evaluating the visibility risks associated with a prescribed burn.

Getting Started

About this Manual

This manual has been divided into eight major sections to encourage and facilitate user review.

- Getting Started describes topic arrangement, system requirements, and help availability.
- Overview provides essential background information.
- Six Major Model Components thoroughly review the scientific basis of VSMOKE.
- Installing VSMOKE discusses how to obtain, install, and test the program.
- VSMOKE Program Characteristics presents general programming information, specific input instructions, and output organization and application.
- Literature Cited lists additional reference materials.
- Index provides quick access to specific topics.
- Appendixes present input examples, output layout, and an output data index.

System Requirements

VSMOKE is written in the FORTRAN 77 programming language and fully conforms to the standards of the American National Standards Institute (ANSI) X3.9.1978 (full language). (See ANSI 1978). VSMOKE was developed and tested on both the USDA Forest Service Data General MV4000 computer system, under IS-CLI, AOS/VS F77 FORTRAN 77, Revision 04.02 Data General (DG); and on an 80386 IBM-compatible personal computer (PC), under MS-DOS, Version 5.0, using Microsoft FORTRAN, Version 5.0, and invoking the 80387 math co-processor (PC). This release of VSMOKE is supported on the PC-compatible environment only; however, its development on the Data General helps ensure that the program will work on a wide variety of systems. The near universality of the FORTRAN language and the program's use of standard syntax also assure wide applicability.

In the PC environment, version 19950128 of the VSMOKE source code takes up 246,909 bytes; the object code (compiled using the PC "4Yb" option) is contained in 3 segments of 6,373, 73,486, and 69,459 bytes; and the executable code takes 155,138 bytes. At least 3 Megabytes (MB) of storage should be available to hold the VSMOKE! source, object, and executable code, while allowing some room for a modest library of input and output files. More extensive libraries will require additional space. Allocating a directory for housing VSMOKE and its associated files is advised.

VSMOKE execution times were rapid in the tested environments. Program processing times averaged less than 1 second per analyzed period when crossplume sightline estimates were not calculated, and averaged about 3 seconds per period when sightline estimates were included. In the 80386 PC environment, a mathematical co-processor (80387) is needed to attain rapid execution times. Such co-processors are integral to more recent PC systems such as the 486. The co-processor is also required to maintain program accuracy.

Getting Help

The exact procedures for setting up and running FORTRAN 77 programs will vary considerably among host system environments. Host system environment refers to the computer hardware and software systems that include the operating system, Fortran compiler, linker, libraries, mathematical co-processor, and other specifics involving the executable code, including its interaction with input and files-some of which cannot be directly specified by the Fortran source code. These complexities prevent prediction of the exact behavior of VSMOKE within an untested environment. Fortunately, both the highly transportable nature of the FORTRAN 77 programming language and VSMOKE's adherence to the ANSI Standard for the language maximize the uniformity of the behavior of VSMOKE in a variety of computational environments. Thus, necessary adaptations to non-PC enviromnents should be minimal,

Users should be familiar with the behavior of FORTRAN 77 programs on the host system before setting up and running VSMOKE. Users wanting more details on implementing VSMOKE as a computer program than this manual provides should consult the FORTRAN 77 computer code. The code is accompanied by numerous comments that explain the mathematical and scientific aspects of the program, program structure, input/output procedures, etc.

Overview

VSMOKE is primarily a tool for analyzing the effects of a single prescribed fire. Using an emissions source geometrically configured to match that presented to the atmosphere by a prescribed fire, the program estimates smoke concentrations and crossplume sightline characteristics at specified downwind distances from the fire. Current scientific knowledge and data acquisition of the operational environment limit the applicability of VSMOKE sightline estimates to relative humidities less than 70 percent. VSMOKE also calculates two indexes that further support the single fire analysis by providing a context for evaluating smoke from multiple fire activity and the risk of smoke-related traffic hazards. These two indexes are also applicable in humid conditions when VSMOKE single fire sightline estimates tend to be unreliable.

VSMOKE uses a steady-state, period-by-period, Gaussian plume analysis to estimate downwind smoke concentrations and visual characteristics. The period-by-period analysis allows fire characteristics and the atmospheric environment to undergo considerable change during the course of a run. As with many U.S. EPA (1986, 1987) dispersion models, each period is considered independently. VSMOKE stores each period's data for a worst-case summary analysis.

VSMOKE is designed to be used either alone or as a component within a system of automated prescribed fire management aids (e.g., as part of a batch programming job). Scientifically definable processes readily calculable from available input data are represented within VSMOKE. However, some modeling compromises are necessary. "Best estimates" are provided when the physics of the problem are relatively well understood. "Conservative estimates" assume the worst and are provided when the physics are poorly understood or their mathematical representation is too complex or time consuming for rapid execution in an operational environment. To help account for uncertainty in current knowledge, flexibly designed input variables allow preliminary or even speculative assessment.

VSMOKE uses a single input file to obtain all required data. The input format has been kept as flexible as possible within the standard FORTRAN 77 programming language processing requirements. Extensive error detection procedures are employed on the input data set, with provisions for immediate screen-based feedback and more permanent file output when problems arise with any input value.

VSMOKE output goes primarily to a single file, with auxiliary end-of-run and error messages also output to the screen. The VSMOKE output format facilitates using automated post-processor programs (such as graphical display programs) while maintaining a presentable printout appearance. VSMOKE output is listed in three sections: an "echo-print" of all data successfully read into the program, a period-by-period analysis, and a worst-case summary constructed from the period-by-period analysis.

VSMOKE consists of six major computationally oriented components:

1. Optional modeling of pollutant constituents and heat emissions, and the initial vertical and horizontal distribution of smoke; the user may input the necessary data (perhaps from a forestry fuels emissions model), or use the simple emissions model contained in VSMOKE.

2. A plume rise model, integrated with the input specifications of the proportion of smoke subject to plume rise and the vertical distribution to be assigned due to plume rise effects.

3. A conventional steady-state Gaussian plume atmospheric dispersion model that yields estimates of smoke concentrations at a number of distances directly downwind from the fire.

4. A crossplume sightline characteristics model that yields visibility and contrast ratio estimates for the plume at the same downwind distances; these estimates are valid only if the ambient relative humidity is below 70 percent.

5. An area-wide dispersion rate model that yields a Dispersion Index (DI).

6. A statistical model of the observed proportion of low visibility occurrences at Florida accident sites, which yields a Low Visibility Occurrence Risk Index (LVORI).

These components are interrelated as smoke hazard management aids and, in some cases, are closely related mathematically. The interrelationships are summarized in the following list:

- Component 1 directly contributes to estimates yielded by components 2 and 3.
- Component 2 directly contributes to estimates yielded by component 3.
- Component 3 directly contributes to estimates yielded by component 4.
- Some mathematical association is present between output variables from components **2, 3,** and 4 and the indexes yielded by components 5 and 6.
- Component 5 directly contributes to the index yielded by component 6.

VSMOKE procedures are relatively simple and computationally efficient. The conservative nature of VSMOKE estimates allows the model to be used as a screening system to point out the potential for smoke-related hazards. Where potential smoke problems are indicated, more mathematically complete models can be run to better describe the nature of the hazard. **INPUFF,** Version 2 (Petersen and Lavdas 1986) is a more complete dispersion model that considers the effects of wind variations in space and time. The PLUWE II model (Seigneur and others 1984) provides more complete visibility analysis oriented to plumes from industrial stacks. These models demand more input requirements and computer resources than VSMOKE, and may not adequately represent the geometry of a forestry-prescribed fire smoke source. Although **INPUFF,** Version 2 can accommodate prescribed fire emissions in most respects, it does not account for "gradual" plume rise (i.e., rise as the smoke leaves the vicinity of the fire).

VSMOKE is based on weather conditions and smoke-related problems found in the Eastern United States. VSMOKE smoke concentration and sightline characteristics estimates can be applied cautiously in the West, but the spatial variability of **windflow** over rugged terrain will limit the plume model's effectiveness. VSMOKE DI estimates are based on widely applicable physical principles and should be applicable to any location. The LVORI is based on statistics **from** Florida and cannot be applied indiscriminately to other locations. However, subjective evidence gained from experience in forecasting and monitoring LVORI does suggest that the risk pattern indicated by the Florida data can be directly applied to those humid areas within a few hundred miles of the Gulf Coast that are capable of sustaining a forest.[1]

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[1] Personal communication, G. W. **Rippen.** 1991. Meteorologist, Georgia Forestry Commission, Macon, GA.

Scientific Basis— Six Major Model Components

Smoke and Heat Emissions and Initial Smoke Distribution

Fundamentally, VSMOKE is **not** an emission model; it is a meteorologically oriented model that uses information **from** other available models that best describe the emissions and plume behavior of a ground fire. Research in forest fuels, fire behavior, and the chemistry of smoke production is reflected within VSMOKE primarily by its input requirements. Because research has not yet led to ubiquitous emissions models for all **fuels** and burning conditions, a simple emissions calculation procedure has been incorporated within **VSMOKE** as a "fall back" option. However, the option to input emissions data on a period-by-period basis should be used whenever the necessary data are available. VSMOKE input requirements are based on the **Sandberg** and Peterson (1984) Source Strength model for Coniferous Logging Slash in the Pacific **Northwest.**[2] This model yields particulate matter, carbon monoxide, and heat emissions estimates on a period-by-period basis, simulating emissions behavior through the complete life of a fire, from ignition to smoldering. Using other emissions models or assumptions is acceptable if all VSMOKE input requirements are met.

If period-by-period emissions data are unavailable, VSMOKE uses an extension of the method developed by Lavdas (1982) to **estimate** smoke and heat emission rates during the course of a fire. This method was also developed from **forestry-**prescribed burning data in the Pacific Northwest-an analysis of burning activity near the Wilhunette Valley, Oregon and its effects on particulate matter concentrations within the valley. Figure 1 shows time dependence of fire characteristics assumed in VSMOKE.

FIRE PARAMETER ASSUMPTIONS

Smoke emissions rate	Held constant for a given duration, TCONST, then undergoes exponential decay (as specified by the decay constant, **TDECAY)**
Heat emission rate	Held constant for a given duration, THOT, not to exceed TCONST, then assumed to be zero.

Figure 1—Time dependence of fire characteristics assumed in VSMOKE

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[2]The current version of the Source Strength model is referred to as the Emission Production Model (EPM). This model yields period-by-period estimates of particulate matter in the 2.5 and 10 micrometer size classes as well as for total particulate matter, carbon monoxide, carbon dioxide, and hydrocarbons (CH,)The model also provides total heat release rate estimates in BTU's per second; these must be converted to megawatts (mw) before they are used in VSMOKE (1 BTU/sec = 1.055 1 $*10^{-3}$ mw). Version 1.02 of EPM handles bums in selected fuel types in Oregon and Washington on both sides of the Cascade Divide. (Personal communication. 1991, 1995. Roger Ottmar, Acting Project Leader, USDA Forest Service, Pacific Northwest Research Station, Seattle, WA.)

Mathematically, the time dependency of smoke and heat emission rates of the built-in VSMOKE model are expressed as follows:

$$SMPEAK = a\ constant \tag{1}$$

$$SMDCAY = \left(SMPEAK\ e^{\left[\frac{(TSIM-TBGDCY)}{TDECAY}\right]}\right) \tag{2}$$

$$HRPEAK = a\ constant \tag{3}$$

$$HRDCAY = 0.0 \tag{4}$$

where

SMPEAK = peak smoke emission rate (during **TFIRE** to **TFIRE** + TCONST interval),
SMDCAY = smoke emission rate during smoke decay period,
HRPEAK = heat emission rate (during **TFIRE** to **TFIRE** + THOT **interval),**
HRDCAY = heat emission rate thereafter (set to zero),
TFIRE = fire start time in hours as input,
TCONST = period of constant emissions in hours as input,
TSIM = model simulation time in hours,
TBGDCY = **TFIRE** + TCONST,
TDECAY = exponential decay coefficient in hours as input, and
THOT = period of sign&ant convective heat emission in hours as input.

This technique as applied in VSMOKE can yield period-by-period smoke emissions estimates that tend to follow those given by **Sandberg** and Peterson (1984). The applicability of the technique outside the Pacific Northwest has not been specifically verified. However, by using user input for the three time parameters in a time-dependent modeling context, **VSMOKE** time-dependent emissions estimates may be applied with a degree of confidence comparable to the input estimates themselves.

Other user input data characterize the geometric configuration of the fire as an emissions source to the atmosphere. The initial geometric configuration is **defined** by the following:

1. Specification of the area of the smoke source **(ACRES[3]).** VSMOKE generally constructs its emissions source as a line at the downwind edge of a square of size matching the user input; a zero or negative input value directs the model to construct a point as an emissions source.

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[3] **The capitalized names in parentheses correspond to the variable names discussed in "VSMOKE Input."**

2. Specification of any initial Gaussian dispersion of the pollutants in the horizontal **(OYINT(I)[3])** and vertical **(OZINT(I)[3])** directions present at the source site. These initial coefficients can be used to characterize how turbulence and flow patterns near the fire **affect** the distribution of nearby smoke on a period-by-period basis. For example, heat at a smoldering burn site might be expected to result in modest lifting of some smoke within the site, but might be too difficult to calculate by using plume rise modeling techniques. Observed effects of low heat output on the vertical smoke distribution at the site can be accounted for by specifying an appropriate value for initial vertical dispersion.

3. Specification of the distribution of smoke **affected** by plume rise. This specification strongly **affects** the initial vertical distribution of pollutants when plume rise occurs. (For additional information, see Plume Rise and Vertical Smoke Distribution.)

Specification **(1)** and the horizontal portion of specification (2) determine the "initial" horizontal distribution of pollutants, while both the vertical portion of specification (2) and specification (3) determine the "initial" vertical distribution. Specification (2) also yields initial Gaussian dispersion coefficients for the fire at the fire site, which are applied to all subsequent model calculations. In contrast, specification (1) yields an initially horizontally uniform distribution along the complete length of the effective line source. Specification (3) can yield either a point source at the calculated plume rise height or a vertically uniformly distributed source. Specification (3) also determines the proportion of smoke emissions **affected** by plume rise. Any remaining smoke is treated as ground-based emissions. These distributions are **further** acted upon by the transport-related dispersion processes in VSMOKE described in Smoke Concentrations.

Plume Rise and Vertical Smoke Dbtribution

In VSMOKE, plume rise is the height smoke emissions reach as a result of convective effects from the fire's heat emissions. Smoke concentrations at ground level, especially those close to a fire, are extremely sensitive to plume rise effects. In particular, the presence of smoldering smoke sources, which lack the necessary heat to generate significant plume rise, creates a potential for excessive nearby ground level concentrations (SFFLP 1976, Lavdas 1978). This ground smoke can be a major contributor to **traffic** accidents (National Wildfire Coordinating Group 1985). Accordingly, VSMOKE uses a pragmatic, concentration-estimate-based, bottom-line philosophy with respect to plume rise estimates similar to that expressed by Briggs (1975) who stated, **"I** prefer to define plume rise as [the value] one would need in the diffiion equation to correctly calculate the maximum ground concentration." VSMOKE includes unique descriptor input variables for plume rise and plume rise associated effects on the initial vertical distribution of smoke. These variables are designed to help the model correctly depict **ground-**level concentrations as a **function** of downwind distance **from** a fire.

VSMOKE relies on plume rise equations developed for industrial stacks to determine the potential height of smoke due to heat emissions **(Briggs, 1969, 1972,** 1975). VSMOKE also includes an option for setting the vertical distribution of smoke resulting from plume rise effects. The vertical distribution may be set to leave a portion of smoke on the ground to distribute smoke uniformly from the ground to the calculated plume height, or both.

Plume rise, as estimated by Briggs, is a function of buoyancy flux, atmospheric stability, and downwind distance. In VSMOKE, buoyancy flux, F, is a function of the total heat emission rate of the fire, Q_H. Q_H is the product of the total fuel mass loss rate within the fire times the heat value of the fuel. Following SFFLP (1976), the heat value of the fuel is 0.014651 Joules per gram (or in SFFLP' units, 3500 calories per gram). Briggs (1975) developed the following equation[4] for buoyancy flux:

$$F \cong \frac{G\, Q_H}{\pi\, C_p\, \rho\, T} \tag{5}$$

where

F = buoyancy flux (due to the heat emissions of the pollution source) in meters raised to the fourth per seconds raised to the third,
G = acceleration of gravity,
Q_H = total sensible heat emission rate,
C_P = specific heat of atmosphere,
p = density of the atmosphere, and
T = temperature of the atmosphere.

In VSMOKE, equation (5) is simplified by assuming:

1. The ideal gas law, i.e., P = ρRT, (where P is atmospheric pressure and R is the gas constant for dry air).

2. The diatomic molecule ideal gas assumption that $\frac{R}{C_p} = \frac{2}{7}$.

3. Standard atmosphere at sea level values for G and P; 9.80665 ms^{-2} for G and 101,325 pascals (i.e., 1013.25 mb) for P.

These assumptions yield the following approximate equation for F in VSMOKE:

$$F \cong 8.8021\, Q_H \tag{6}$$

where

Q_H is expressed in megawatts.

[4] Equation 11, page 63, of Briggs (1975).

Once an estimate of buoyancy flux is obtained, the appropriate plume rise equations can be selected. First, the value, DTHETA, of the vertical potential temperature gradient (a measure of atmospheric temperature change with respect to height above the ground) is used to select an equation for predicting final plume rise. If DTHETA is at least 0.001 K m^{-1}, indicating stable conditions, the following two equations are **evaluated** to yield "candidate" final plume rise estimates. (NOTE Definitions of variables for equations (7) through (12) are given on pages **11-12.)**

Final plume rise equation for DTHETA $\geq$ 0.001 K m^{-1} in most wind conditions is:

$$H_{FS} = 2.\left[\frac{F}{U_T S}\right]^{\frac{1}{3}} \tag{7}$$

Final plume rise equation for DTHETA $\geq$ 0.001 K m^{-1} in very light winds is:

$$H_{FLW} = 5.0 F^{\frac{1}{4}} S^{-\frac{3}{8}} \tag{8}$$

where, in equations (7) and (8)

$$S = 9.80665\left(\frac{DTHETA}{THETA}\right) \tag{9}$$

An additional "candidate" fmal plume rise estimate is **evaluated** if the atmospheric conditions are regarded as stable. This same estimate produces the only "candidate" fmal plume rise estimate if the vertical potential temperature gradient, **DTHETA,** is less than 0.001 K m^{-1}, i.e., indicating a neutral or unstable atmosphere. The choice of equations to produce this estimate is based on the value of the estimated buoyancy flux, **F** (from equation **(6),** or more generally, equation **(5)):**

For $F \leq 5\ 1.602\ m^4\ s^{-3}$:

$$H_{FNUS} = 21.425 F^{\frac{3}{4}} U_T^{-1} \tag{10}$$

For F > 51.602 $m^4\ s^{-3}$:

$$H_{FNUS} = 38.710 F^{\frac{3}{5}} U_T^{-1} \tag{11}$$

The following scheme is used to select the "winning candidate estimate" for final plume rise, HF, (i.e., the plume rise ultimately attained as the plume moves downwind) from the various applicable "candidates":

1. **If DTHETA $\geq$ 0.001 K m^{-1} <u>AND</u> F $\leq$ 51.602 m^4 s^{-3}, H_F = the minimum of H_{FS}** (from equation **(7)), H_{FLW}** (from equation **8)),** or **H_{FNUS}** (from equation (10)).

2. If DTHETA $\geq$ 0.001 K m^{-1} **<u>AND</u>** F $>$ 51.602 m^4 s^{-3}, H_F = the minimum of H_{FS} (from equation **(7)), H_{FLW}** (from equation **(8)),** or **H_{FNUS}** (from equation (11)).

3. If DTHETA $<$ 0.001 K m^{-1} **<u>AND</u>** F $\leq$ 5 1.602 m^4 s^{-3}, H_F = H_{FNUS} (from equation **(10)).**

4. If DTHETA $<$ 0.001 K m^{-1} **<u>AND</u>** F $>$ 5 1.602 m^4 s^{-3}, H_F = H_{FNUS} (from equation **(11)).**

5. An additional restriction on the value of H_F is placed, regardless of the value of **DTHETA <u>OR</u> F: H_F** may not exceed the input value of mixing height, A_{MIX}.

Generally, the plume rise used in subsequent model calculations in VSMOKE is also allowed to be a function of downwind distance. That is, the model smoke plume usually climbs as it is transported downwind until **final** plume rise is attained. For a strictly limited type of VSMOKE application, including the effects of gradual plume rise with respect to downwind distance may not be necessary. However, for most operational applications of VSMOKE, the gradual plume rise **option**[5] compares the fmal plume rise estimate, H_F, to the partial plume rise estimate, H_{PART}, based on the Briggs (1975) **"2/3** distance dependent law." The lower of the two **values** is applied to subsequent model calculations for that specific downwind distance.

The Briggs **"2/3** distance dependent law" partial plume rise, H_{PART}, estimate is independent of DTHETA, i.e., it is used for all atmospheric stabilities. The following equation estimates H_{PART}:

$$H_{PART} = 1.6\ F^{\frac{1}{3}} (1000\ X_{KM})^{\frac{2}{3}}\ U_T^{-1} \tag{12}$$

where separate estimates of H_{PART} are made for each downwind distance, X,.

Definitions of variables for plume rise equations (7) through (12) follow:

H_F = "final" plume rise in meters,
H_{FNUS} = **"final"** plume rise generally in near neutral or unstable conditions,

[5] **This option is controlled by the variable, LGRISE. See VSMOKE Input Requirements (page 78) for more information.**

H_{FS} = "final" plume rise for most stable conditions,
H_{FLW} = "final" plume rise in stable, very light wind conditions
H_{PART} = "partial" plume rise in meters,
S = a stability parameter in inverse seconds squared,
DTHETA = vertical potential temperature gradient in degrees Kelvin per meter; in **VSMOKE,** DTHETA is assigned a zero value if the stability class is unstable, or near neutral during the day; at night, **DTHETA** is set to 0.010 for near neutral stability, 0.020 for slightly stable conditions, and 0.035 for moderately or extremely stable conditions (stability class, itself, is either defined by input or determined from other input data within the model),
THETA = representative potential temperature in degrees Kelvin (defined by input),
U_T = transport windspeed in meters per second for the period, as used in plume rise calculations (not allowed to be less than 0.5 meters per second) (defined by input),
X_{KM} = downwind distance in kilometers, and
A , = mixing height in meters (defined by input).

Because the Briggs plume rise equations were developed for tall stacks, the modeling of plume rise from ground fires must be approached cautiously. In tall stacks, smoke and heat emissions are directly associated with each other, while in ground fire, extensive areas of smoldering (with high smoke emissions but little significant heat production) may be well removed **from** actively flaming areas. One relevant theoretical question was formulated: "Is direct and complete involvement within a single convection column observed for all smoke generated **from all** possible geometric configurations of ground fires?" Numerous informal and formal observations (SFFLP 1976) yielded a "No" answer, at least for low or moderate intensity prescribed fires (or for high intensity fires as they are dying). Accurately predicting ground fire plume rise remains uncertain because estimates of plume rise based on stack data may not be applicable and the proportions of smoke that ultimately undergo complete, incomplete, or insignificant plume rise are largely unknown.

The practical smoke management implication of the plume rise prediction problem is that at least a fraction of the smoke from a ground fire may be close enough to the ground to result in potentially high ground-level smoke concentrations near the fire. Hazardously high smoke concentration values might not be picked up by dispersion model estimates unless suitable adjustments are made to the model's plume rise equations, dispersion equations, or both. Any dispersion model for a ground fire using the unmodified Briggs stack plume rise equations is likely to greatly underestimate the potential hazard from ground level smoke near the source.

In the first attempt to quantifiably evaluate this problem, Lavdas (1978) tested the Briggs equations against vertical smoke distribution data obtained **from** three **low-**intensity test fires by aircraft nephelometer sampling. Fire and atmospheric parameters for the test fires fell into the following ranges: buoyancy fluxes (values of F as given by equation (6)) from about 300 to 1,000 $m^4 s^{-3}$, line lengths from 80 to 200 meters (m) within areas of about 1.75 to 10 acres, fuel consumed mostly to totally by a single line of fire, and transport windspeeds from 5 to 12 ms^{-1}. The Briggs formulas excelled in predicting maximum observed height of smoke from these fires. However, significant amounts of smoke were found well below the predicted height, some near the ground. Based on optimizing the performance of the Gaussian plume model in predicting smoke concentrations near the ground using Pasquill-Gifford-Turner dispersion coefficients (Turner 1970), Lavdas (1978) proposed allowing 60 percent of the smoke to rise to Briggs' height, while leaving 40 percent to disperse from ground level. This modification to the plume rise equations resulted in a good fit to observed ground-level concentrations near a fourth test fire. A recent, unpublished analysis[6] tested the effect of a curtain-like vertically uniform distribution of smoke from the ground to Briggs' plume height for 75 percent of the smoke, while leaving 25 percent to disperse from ground level. This distribution resulted in a slightly better fit for predicted ground level smoke concentrations and a much improved description of the observed vertical profiles of smoke.

To accommodate these limited findings and the heuristically reasonable extrapolations from available information and observations of plume behavior effects on ground-level concentrations, VSMOKE adds the following user-input-driven specifications,[7] which greatly extend the Lavdas (1978) formulation:

1. Specification of the proportion of smoke (i.e., from zero to one) subject to plume rise processes.

2. Specification of whether the rising portion of smoke is to be dispersed solely from Briggs' height or as if from a uniform "curtain" extending from the ground to the Briggs height.

Any smoke not subject to plume rise processes is left to disperse from ground level.

The ability of the VSMOKE model to accommodate a single, initially vertically uniform source within a surface-based vertical layer is unique among plume dispersion models. Gaussian plume dispersion effects on the initially uniform vertical "curtain" of smoke are calculated as the smoke is transported downwind with reference to plume concentrations at ground level. (See Smoke Concentrations for more information.)

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[6] Lavdas (1991) unpublished analysis.

[7] The two specifications are controlled by a single user input variable. If period-by-period emissions data are available (i.e., if LQREAD is TRUE), the controlling variable is EMTQR(I), which is specified on a period-by-period basis. If such data are not available (LQREAD=FALSE), the controlling variable is RFRC. In either case, the valid range of values is from -1 to +1. Its absolute value controls the proportion of smoke subject to plume rise, while its sign controls the vertical distribution assigned to plume rise associated smoke. See the VSMOKE Input Requirements, Input Variables for more information.

A third plume-riserelated specification determines whether the **final** plume height is reached immediately or gradually as the smoke travels downwind (i.e., whether or not the downwind distance-dependent plume rise value, $\mathbf{H_{PART}}$, is considered in the plume rise estimate). Gradual plume rise effects normally should be calculated. The alternative option forces the final plume rise value, $\mathbf{H_F}$, to be used at all downwind distances and is primarily intended for occasions when benchmark runs of **VSMOKE** may be required for models that do not include gradual plume rise in their calculations. For example, certain puff models **(INPUFF,** 2.0) (Petersen and Lavdas 1986) are designed to include the effects of varying wind flow on smoke transport and dispersion, but use the final plume rise value for the height of all puffs. Although such puff models are less physically realistic in terms of plume rise calculations near the source, they can depict changing wind conditions, spatially varying wind conditions, or both more realistically than VSMOKE can.

Combining the various plume rise related specifications with the specification of initial vertical dispersion, gives VSMOKE considerable flexibility in specifying the overall initial distribution of smoke in the vertical dimension (fig. 2). If all smoke undergoes "significant plume rise", little or no smoke is present at ground level for some distance downwind (fig. 2, part A). In the split plume rise option ground smoke is present at all downwind distances (fig. 2, part B); however, the vertical profile of smoke near the **fire** is often unrealistic. The smoke curtain option (fig. 2, part C) often improves the realism of the vertical smoke profile and can be used to approximate the effects of gravitational settling of larger smoke particles in the plume. This last option also may include ground smoke.

VSMOKE is designed to readily accommodate revisions in the methodology for calculating and, to some extent, utilizing plume rise. Current knowledge is scanty, and independent investigations may yield significantly different results. The sensitivity of VSMOKE estimates to plume rise assumptions and model input values is very high, particularly near the **fire** in stable conditions (i.e., under conditions in which potential hazard is greatest). Therefore, the effect of any plume rise revisions on the "bottom line" smoke concentration estimates of VSMOKE should be carefully considered before they are used in an operational environment.

Smoke Concentrations

Selecting a Dispersion Model

The largest single computational component within the VSMOKE computer code is its singlesource, steady-state, Gaussian plume atmospheric dispersion model. To visualize such a model, imagine a uniform air mass with steady wind direction and speed. Any pollutant will be carried downwind by this mean wind. The Gaussian plume model assumes that the uniform wind flow is disturbed by small random perturbations (i.e., wind fluctuations such as gusts, lulls, and momentary wind shifts). The character of these perturbations causes measurements of pollutant concentrations along a cross-section at right angles to the mean wind to assume a Gaussian shape.

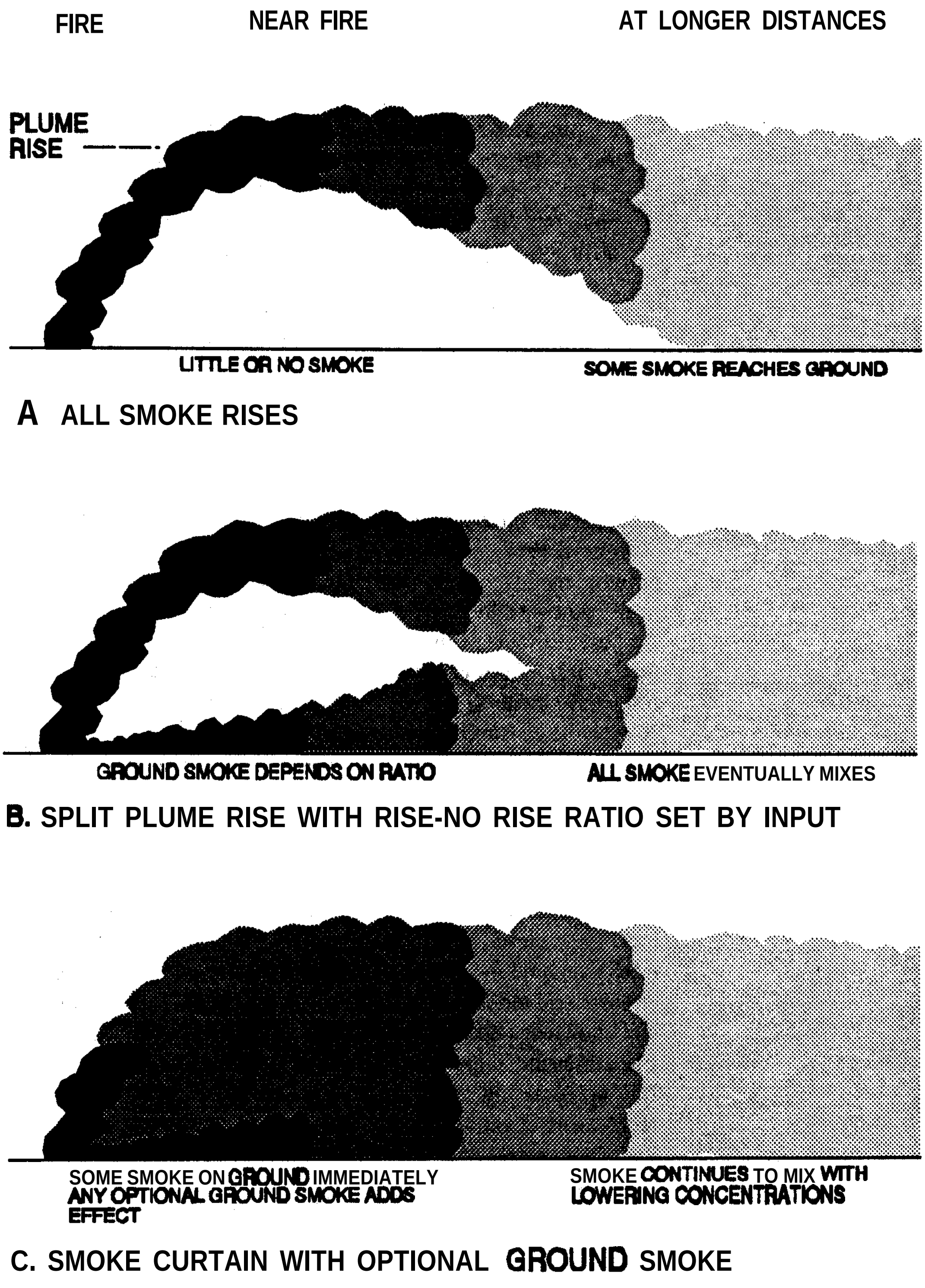


Figure 2-Effects of plume rise options on smoke concentrations at the ground.

Hanna and others (1982) provide a generic description of the Gaussian plume model and compare this modeling approach to some of the more mathematically comprehensive and demanding dispersion modeling techniques. The following remarks summarize their assessment of the Gaussian plume model:

> ". . . is still the basic workhorse for dispersion calculations; . . . produces results that agree with experimental data as well as any model; . . . is a relatively easy framework to mathematically solve; . . . is appealing conceptually; . . . is consistent with the random nature of turbulence; . . . is a solution to the Fickian diffusion equation" . . . has found its way into most government guidebooks, thus obtaining a 'blessed' status;" and [although it contains much empiricism] ". . . other so-called theoretical formulas contain large amounts of empiricism in their final stages."

Traced back to the work by Taylor (1921), the Gaussian plume model has been refined by many: Sutton (1947), Pasquill(1961, 1974, 1976), Gifford (1961), Turner (1964, 1970), and Irwin (1983). Continuing research tends to confirm that the Gaussian plume model is no longer "state of the art" (Venkatram and Wyngaard 1988). Yet, the difficulty in obtaining the data required to run more accurate models-particularly on an operational, real time basis--leaves significant gaps between theoretical representations of atmospheric motions and the best available means of operationally characterizing them from available data in real time. Currently, for many air quality analyses needs, the Gaussian plume dispersion model is still a "workhorse." As recently as 1987, in the U.S. EPA's "Guideline to Air Quality Models" (U.S. EPA 1986, 1987) nearly all U.S. EPA "preferred models" and the majority of "alternative models" were based on the Gaussian plume model.

Evaluating the input requirements of a dispersion model is a particularly relevant problem for forestry-prescribed burning. Prescribed fire is a relatively inexpensive land management tool usually conducted in remote locations. At any given location, a prescribed fire is a transient pollution source. Compared to what is often available for a large stationary pollution source for which specialized atmospheric monitoring is typically available and often mandated, resources for and knowledge about collecting and using meteorological data on site are limited. The atmospheric monitoring of large stationary pollution sources should gradually lead to increasing use of rather sophisticated dispersion models. These models will require and effectively utilize data such as continuous measurements of wind, temperature, pressure, and moisture variations in vertical and small horizontal scales; direct measurements of turbulent parameters such as very short-time-scale fluctuations of horizontal and vertical wind; and various means of describing site

[8] A very simple form of the Fickian diffusion equation states that the first derivative of concentration with respect to time is equal to the second derivative of concentration with respect to distance times a diffiivity constant, usually denoted by "K." A more complex, but still incomplete, form uses differing values of K in the downwind, horizontal crosswind, and vertical directions.

and surrounding variables that affect wind flow and turbulence, such as roughness parameters and surface heating coefficients. Models with these data requirements will be of little practical value in real-time operational analysis of smoke from fires at remote locations until technological and theoretical advances provide the means to monitor the required input on a national scale. Even as data sources become more complete, and more complex models are implemented, the Gaussian plume model will probably continue to be used as a screening analysis tool.

The limitations of currently available real time data include its inability to properly define wind fluctuation statistics, characterize vegetative or terrain roughness except in a crude sense, or confidently describe many meteorological variables in the vertical. The Gaussian plume model has several advantages in this type of operational environment, especially when used as a conservative screening tool. It is readily understood by nonmeteorologists; its strengths and weaknesses are well known within the meteorological community and readily communicated to foresters and administrators; its input requirements are relatively well matched to the level of information available in real time at remote forest locations; and it is based on data sets that are particularly well suited for predicting ground-level concentrations near a ground-based pollution source (Briggs 1988). This last advantage is particularly significant, given the roadway safety hazard potential associated with smoldering smoke and the need for a reasonably accurate system to characterize the risk and extent of potential hazard.

VSMOKE does not consider any changes in any of the pollutants during the time smoke travels from source to receptor. The simplest mathematical method of accounting for pollutant removal uses first order decay processes of pollutant constituents. Some Gaussian plume dispersion models use a pollutant exponential decay constant or half-life decay constant (Irwin and others 1985). According to Hanna and others (1982), first order decay can be utilized for some wet deposition (using a scavaging coefficient), chemical transformation processes (using a chemical decay rate coefficient), and radioactive pollutants. VSMOKE makes no allowance for first order decay, and no first order decay effects have been documented for forestry smoke to the author's knowledge. First order decay reduces pollutant concentrations, and if decay effects do occur within forestry smoke plumes, VSMOKE concentration estimates may be too high. Overestimating smoke effects because physical processes are poorly understood or accounted for introduces a degree of conservatism, a desirable tendency in the screening applications for which VSMOKE is designed.

Other processes that may transform or remove pollutants within the atmosphere include settling and deposition. These processes can be modeled by using one or more velocity coefficients, which assume that particles move downward at the given speed(s) as they are transported downwind. Gravitational settling efficiently removes large and dense (massive) suspended particulates, but has no effect on carbon monoxide. Because forestry particulates are relatively small they are less affected by settling than are particulates from urban sources. According to Petersen and Rumsey (1987), dry deposition includes a number of removal mechanisms, including gravitational settling, turbulent and Brownian diffusion, chemical absorption, inertial impaction, and thermal and electrical effects. Some particles may actually be reintroduced into the atmosphere by mechanical resuspension (e.g., a dust storm). The Gaussian plume PAL 2.0 model (Petersen and Rumsey 1987), and Gaussian puff INPUFF 2.0 model (Petersen and Lavdas 1986) are U.S. EPA dispersion models that include the effects of settling and dry deposition. Both models include settling and deposition velocity as input parameters.

The governing equations for deposition and settling processes within PAL 2.0 and INPUPP 2.0 are somewhat complex and time consuming compared to remaining model computations. In INPUPP 2.0, the inclusion of dry deposition and settling effects considerably increases computational time. A test that included settling and dry deposition velocities thought to be characteristic of forestry smoke (Chi and others 1979, Buck 198 1) did not have a decisive effect on INPUFF 2.0 smoke concentration estimates. Deposition and settling computations are not included in VSMOKE because: (1) they are relatively demanding, (2) their effect is to lower aggregate smoke effects at any given distance from the fire, and (3) any tendency they might have to increase smoke effects at ground level near the fire can be simulated by simple adjustments of VSMOKE input parameters.

Other pollutant transformation and removal processes, such as wet deposition modeling, are mote difficult or even impractical to include in a steady-state plume model. Some wet deposition modeling techniques use washout ratio which, in a limited way, can defme a wet deposition velocity analogous to dry deposition velocity. This type of wet deposition can be incorporated in a steady-state plume model. However, most photochemical transformation modeling, used for urban area pollutants such as ozone, uses chemical kinetic relationships within the framework of gradient transfer models-a very different framework from that used in VSMOKE.

The steady-state Gaussian plume model context is used in VSMOKE because it has a good track record and is generally accepted, easily understood, adaptable, and compatible with the constraints of forestry field-level planning and real time applications. The Gaussian plume model is also an attractive methodology for "worst-case" analysis in "pre-planning" or "screening" operational environments-such a model can efficiently identify scenarios requiring the use of more precise and demanding computational methodologies. Computational demands preclude the use of settling and deposition adaptations of the Gaussian model, while the desirability of conservative smoke impact estimates precludes the use of pollutant decay coefficients associated with smoke travel distance.

Applicability of the VSMOKE Steady-State Gaussian Plume Dispersion Model

The steady-state Gaussian plume model used in VSMOKE is best suited for considering the effects of a single fire within periods of constant or slowly changing fire, smoke emission, and weather conditions, during which the smoke concentration field can be accurately depicted within a steady-state framework. The period-by-period analysis employed by VSMOKE allows some consideration of changes in fire and weather conditions. However, VSMOKE calculations for any given period are independent of those for any other period, i.e., the weather or emissions of past periods have little direct effect on concentration estimates for the current period.

The Gaussian plume model is based on the idea that while pollutants are steadily and bodily transported downwind by the "mean transport vector" of the wind field, small-scale turbulence disperses the pollutants in directions perpendicular to the mean transport direction. This results in a Gaussian distribution of pollutants with respect to crossplume distance from the plume centerline. Because horizontal and vertical turbulent motions differ greatly, the model calculates two Gaussian coefficients to deal with horizontal and vertical pollutant displacements. The Gaussian plume model is used successfully when the following conditions are met:

- Turbulent motions are of small space and time scale with respect to the mean flow.
- Turbulent motions are sufficiently random.
- Mean flow is uniform, linear, and invariant, or nearly so.
- Mean flow and turbulent structure maintain a sufficient uniformity during the period and across the domain within which pollutant transport and dispersion occurs.
- Resulting horizontal and vertical displacements are correctly characterized.

Placed in a climatological and synoptic meteorology context, these requirements mean that Gaussian plume modeling is generally suitable either within a well mixed "boundary layer" of the lower troposphere- e.g., within a well established surface thermal mixing layer typical of fair weather afternoon conditions in the lowest 1,000 to 1,500 m-or within a shallow, nominally uniform, nocturnal, ground-based, stable layer. The approach, as used in VSMOKE, does not directly delineate mass exchange rates or turbulent processes between adjacent contrasting atmospheric layers (e.g., between a stable surface layer and an overlying neutral or unstable layer). Generally, uniform air masses with uniform flow are required to maintain reasonable model performance. This requirement typically matches the need for predictable and steady fire behavior in prescribed burning operations (Wade and Lunsford 1989). Areas with fair weather within high pressure systems, and locations within relatively linear fields of pressure gradient (e.g., isobars forming nearly straight lines or slowly sweeping arcs on a national weather map), often found around the periphery of high pressure systems, are often well suited for both safe and predictable prescribed fire' behavior and relatively accurate Gaussian plume model estimates. Complicating factors such as rough terrain, sea or large lake breezes, or changing weather patterns can cause model performance to range from degraded accuracy to compromised performance to a point where the model simply "does not work."

Given an appropriate "weather map," the Gaussian model can be expected to often work well in flat or rolling terrain in the Pastern United States. In the Western United States, terrain driven effects often dominate the forces that determine wind flow patterns. Considerable expertise in interpreting regional and local weather patterns is required for any assurance that a plume model will work acceptably for any given location in the Western United States. However, VSMOKE might be used in selected situations, perhaps to establish a basis of comparison in evaluating the performance of more mathematically comprehensive modeling approaches.

The steady-state, period-by-period analysis technique used in VSMOKE allows limited model applicability to scenarios that include changing fire and smoke emissions behavior and changing weather conditions. Each analysis period of VSMOKE should be regarded as a "snapshot" scenario during which **all** fire, emissions, and weather parameters remain constant during the period. Because most input parameters are allowed to vary from period to period, VSMOKE can analyze a series of snapshots for several periods. The modeling approach used in VSMOKE is not suited for rapidly changing weather regimes unless the analysis interval is set short enough to effectively **"freeze"** the weather changes in time and space.

How the period-by-period capability of VSMOKE can be applied may be appreciated by considering a rather typical case of a prescribed fire. Fire personnel ignite a **fire** in an early **afternoon** with moderate winds and a slightly unstable atmosphere (a normal "fair" weather afternoon condition). After the fire actively burns for an hour or two, the personnel (unwisely) allow the fire to smolder for several more hours. The smoldering could easily extend into the night hours, when the winds would drop and a ground-based stable inversion would form. Through the proper specification of input values, a single VSMOKE run can generate smoke concentration estimates during the active period of the fire in the afternoon and during smoldering the following night. The estimates for each of the periods would be identical to estimates generated by properly specified separate VSMOKE simulations for each of the two periods.

Mathematical Basis of the VSMOKE Gaussian Plume Model

Using Turner's (1970) approach, VSMOKE concentration estimates are made at receptor locations along the centerline of the plume trajectory, and are applicable at ground level. The equation for concentration resulting from a single pollutant source as given by the Gaussian plume model under these restrictions may be expressed as:

$$C = \frac{Q}{\pi \sigma_Y \sigma_Z U} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_Z}\right)^2\right] \qquad (13)$$

where

C = concentration due to the source in micrograms per cubic **meter,**

Q = **source** strength emission rate in micrograms per second,

σ_Y = horizontal dispersion coefficient in meters (a ftmction of atmospheric stability and downwind distance),

σ_Z = vertical dispersion **coefficient** in meters (a function of atmospheric stability and downwind distance),

U = transport windspeed in meters per second (as input), and
H = plume height in meters (a function of heat emissions, atmospheric stability, and downwind distance).

Figure 3 shows an idealized depiction of the geometric structure of the Gaussian plume model as described by equation (13). In this figure, a horizontal cross-section with a Gaussian smoke concentration is shown closest to the fire, while the more distant profile shows a vertical Gaussian profile. Please note that the horizontal and vertical dispersion coefficients, a, and σ_Z, need not (indeed, generally do not) have the same **values** at any given downwind distance.

Equation (13) precisely applies in **VSMOKE** only if (1) a point source is specified or may be assumed, (2) a single plume height exists, and (3) the vertical dispersion **coefficient** is small compared to the mixing height (i.e., "reflections" of pollutants from the top of the mixing layer have no appreciable effect on ground-level concentrations). Equation (13) is modified as necessary to accommodate the **VSMOKE** assumption that all pollutants are "trapped" within the surface-based mixing layer, i.e., all pollutants remain at and below the mixing height value, A_{MIX}. **VSMOKE** concentrations within the mixing layer are assumed to undergo perfect and complete "reflections" both from the ground and from the mixing height. If the vertical dispersion coefficient, σ_Z, is much larger than the mixing height, A_{MIX}, the resulting vertical distribution of pollutants is essentially uniform within the mixing layer. In **VSMOKE,** the plume is assumed to be vertically uniformly mixed whenever σ_Z exceeds two times A_{MIX}. The governing equation for a point source in this case may be expressed as:

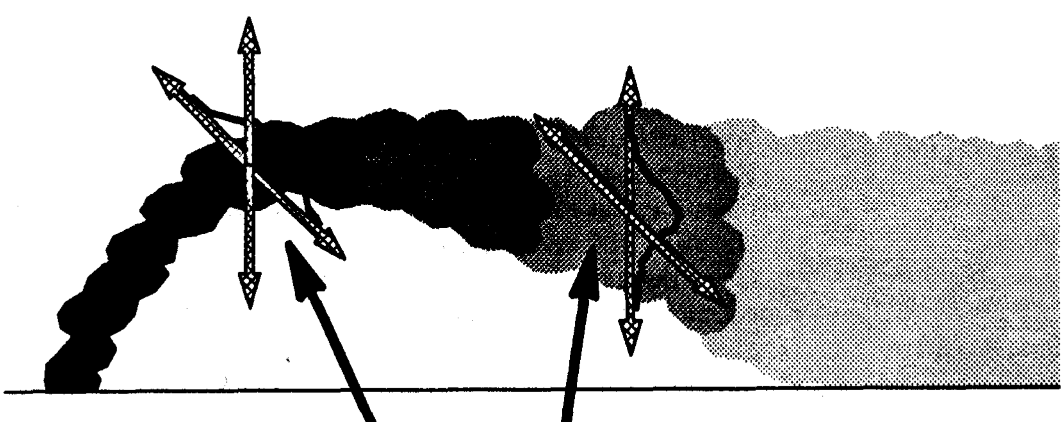


Figure 3—Idealized Gaussian Plume Model.

$$C = \frac{Q}{\sqrt{2\pi}\ \sigma_Y\ A_{MIX}\ U} \qquad (14)$$

For cases in which plume trapping may be important, but a vertically uniform plume has not yet been achieved VSMOKE uses the plume trapping assumption to account for multiple eddy reflections. The governing equation used when a, is no more than two times A_{MIX} **may be** expressed as:

$$\begin{aligned} C = \frac{Q}{2\pi\ \sigma_Y\ \sigma_Z\ U} \Bigg\{ & 2 \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_Z}\right)^2\right] \\ & + \sum_{N=1}^{M} \Bigg\{ \exp\left[-\frac{1}{2}\left(\frac{-H-2\ N\ A_{MIX}}{\sigma_Z}\right)^2\right] \\ & + \exp\left[-\frac{1}{2}\left(\frac{+H-2\ N\ A_{MIX}}{\sigma_Z}\right)^2\right] \\ & + \exp\left[-\frac{1}{2}\left(\frac{-H+2\ N\ A_{MIX}}{\sigma_Z}\right)^2\right] \\ & + \exp\left[-\frac{1}{2}\left(\frac{+H+2\ N\ A_{MIX}}{\sigma_Z}\right)^2\right] \Bigg\} \Bigg\} \end{aligned} \qquad (15)$$

where

M = an integer such that each value to be exponentiated in the series is -25 or less (i.e., all terms $<< 10^{-10}$).

In evaluating equation **(15),** each exponentiation argument is included if it is no less than the criterion value of -25, and the summation process continues until all arguments are less than the criterion. Under VSMOKE constraints which restrict H **from** zero to A_{MIX} and the use of equation (15) only if σ_Z is no more than two **times** A_{MIX}, the summation is completed in eight passes at most and is usually completed in fewer than four passes. When all the terms within the summation are insignificant, equation (15) is equivalent to equation (13). VSMOKE uses equation (15) more than many U.S. **EPA** models, which is a nominal disadvantage in execution time. Because tests on the design host systems revealed that the increased time insignificantly affected operations, the more complete use of equation (15) is executed in **VSMOKE.**

Figure 4 depicts the effects of multiple reflections from the ground and from the top of a mixing layer on concentrations within the mixing layer. The initially Gaussian vertical smoke profile closest to **the** fire is gradually modified as the "tails" of the distribution interact with the upper and lower bounds. These tails are "folded" or "reflected" back into the mixing layer, and their concentration contributions are added to the main portion of the Gaussian plume. As the vertical dispersion **coefficient,** σ_Z, increases to about the same value of the mixing height,

A_{MIX}, a number of such reflections takes place. As σ_Z becomes substantially larger than A_{MIX}, a vertically uniform smoke distribution results.

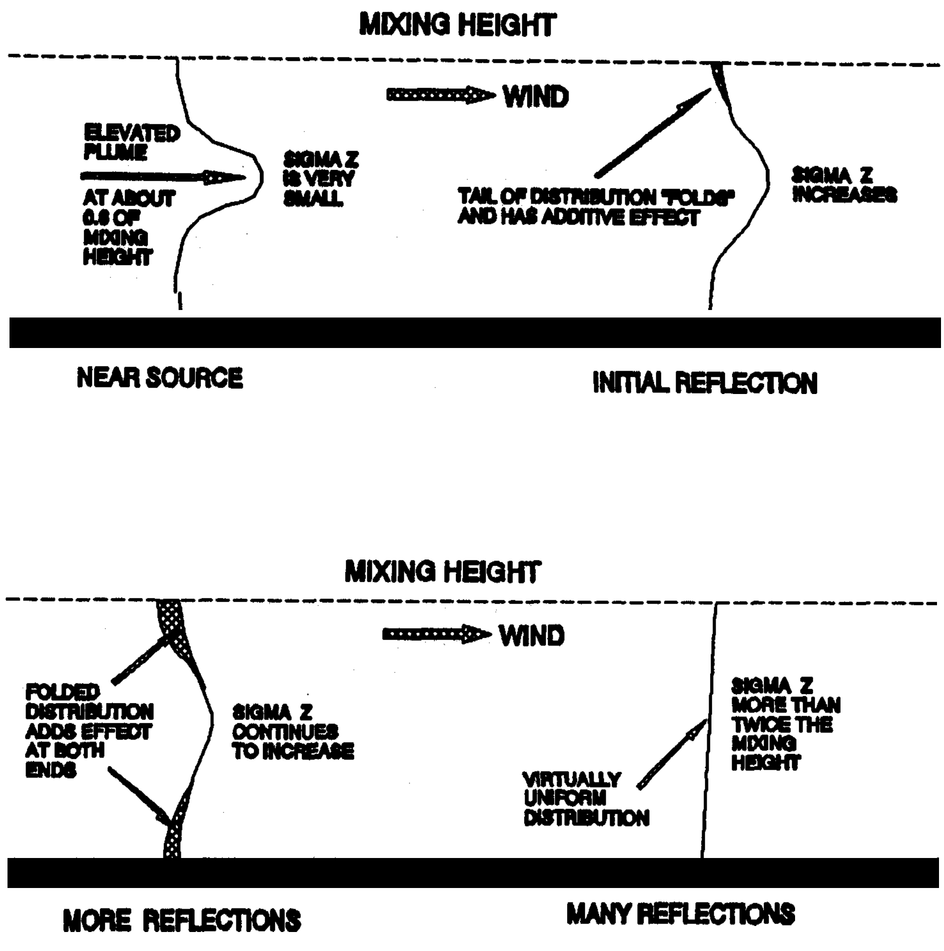


Figure 4—Vertical "reflections" from ground and mixing height "lid" in a Gaussian plume model.

When the ares of the burn is greater than zero, VSMOKE (in most cases) replaces the applicable point source equation with a finite line source equation to estimate concentrations. If the downwind distance from the finite line to the analysis point is sufficiently great, the line "looks like a point." Because the point source equations (13) to (15) are sufficiently accurate, they are used for a finite line source if the effective line length of the source in meters, E_{LINE} (defmed as the square root of the area of the burn in square meters), is no more than 0.012 times the horizontal dispersion coefficient, σ_Y. If E_{LINE} exceeds 0.012 times σ_Y, the source is treated as a uniform finite line source of emissions, and finite line source modeling is used to estimate concentrations. If plume trapping is not important (i.e., if equation (13) would apply for a point source), the governing equation for a finite line source may be expressed as:

$$C = \frac{2Q}{\sqrt{2\pi}\ \sigma_Z\ U\ E_{LINE}} \exp\left[-\frac{\ }{2}\left(\frac{\ }{\sigma_Z}\right)^2 \right] \int_{P_1}^{P_2} \frac{\ }{\sqrt{2\pi}} * \exp\left(-\frac{1}{2}\ P^2\right) dP \qquad (16)$$

where

E_{LINE} = effective line length in meters,
P = the quantity, Y/σ_Y, where Y is **horizontal** crossplume distance from the plume centerline in meters,
P_1 = Y_1/σ_Y, where Y_1 is one of the finite line end points, and
P_2 = Y_2/σ_Y, where Y_2 is the other **finite** line end point.

Iu VSMOKE, all concentration estimates are made directly downwind of the central point of the source, therefore as used in equation (16):

$$Y_2 = 0.5\ E_{LINE};\ Y_1 = -Y_2;\ \textit{thus}\ P_1 = -P_2\ \textit{and}$$
$$P\ \textit{ranges from}\ -0.5\frac{E_{LINE}}{\sigma_Y}\ \textit{to}\ +0.5\frac{E_{LINE}}{\sigma_Y}.$$

The **definite** integral within equation (16) is the inverse normal distribution functionwith respect to P (or Y/σ_Y). VSMOKE uses a polynomial approximation, as described by Abromowitx and Stegun **(1972),** equation **(26.2.17),** to evaluate this integral. The raw mathematical polynomial is accurate to within 7.5 * 10^{-8}, an accuracy maintained within VSMOKE through the use of DOUBLE PRECISION computations as required. Additional information on this aspect of VSMOKE computations is provided within the computer code.

Finite line source effects ate also considered when vertically uniformly mixed plume or plume trapping computations are appropriate (i.e., when equations (14) or (15) would be appropriate for a point source). Because the VSMOKE computer **code** breaks all concentration **calculations** into horizontal and vertical terms, complete equations of the form of equation (16) never appear in the code, and are not included in this discussion. The corresponding governing equations for trapped pollutants from a **finite** line source would bear the same relationship to equations (14) and (15) as does equation (16) to equation (13). Figure 5 depicts the effect of a finite line source on smoke concentration estimates. Close to the source, concentrations are horizontally uniform with a rapid drop to background levels downwind from either edge of the line. As downwind distance increases, these “near step changes” begin to take on a “half-Gaussian curve” shape. As the horizontal dispersion coefficient, σ_Y, continues to increase with increasing distance, these half-Gaussian curves begin to affect the uniform central area. Ultimately, as σ_Y becomes much larger than the length of the line source, the horizontal cross-section of smoke concentration becomes fully Gaussian, as if a point source, rather than a finite line source, were upwind.

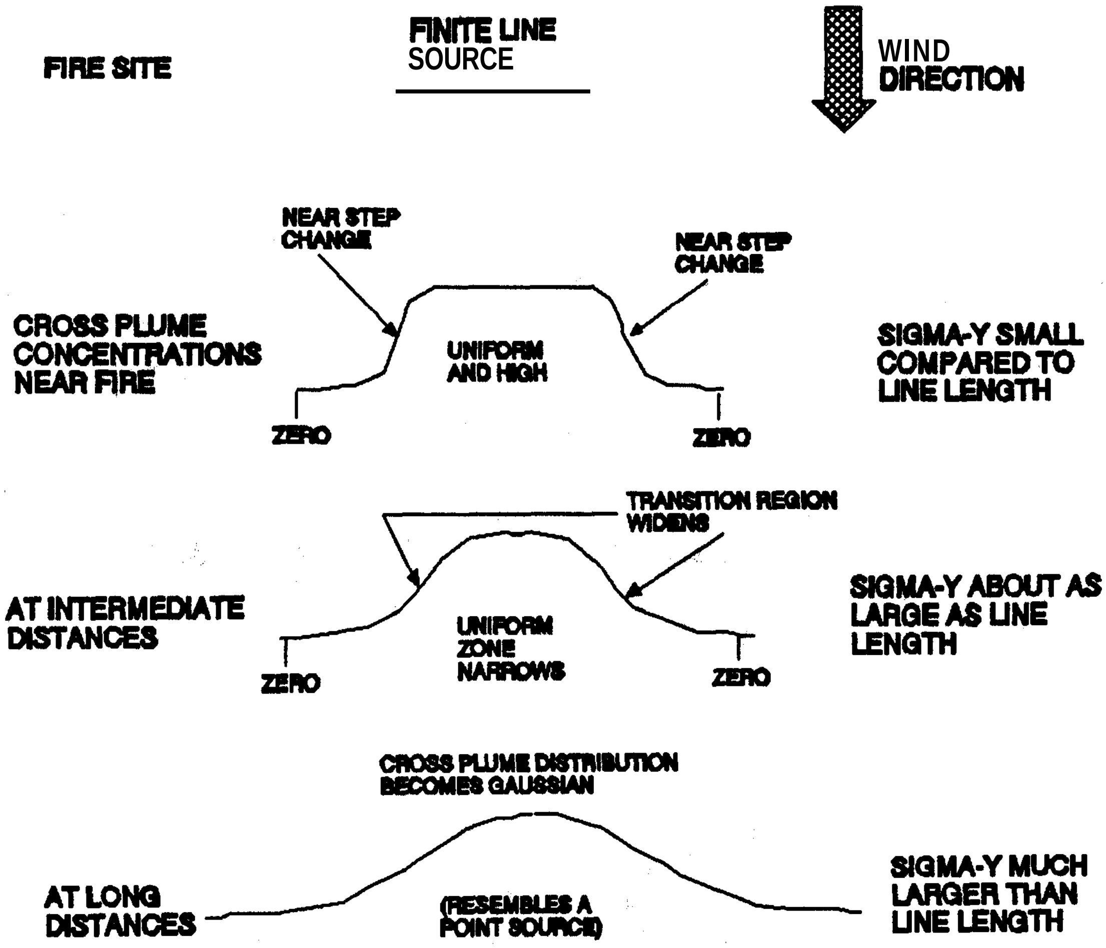


Figure 5—Line sources in a Gaussian Plume Model.

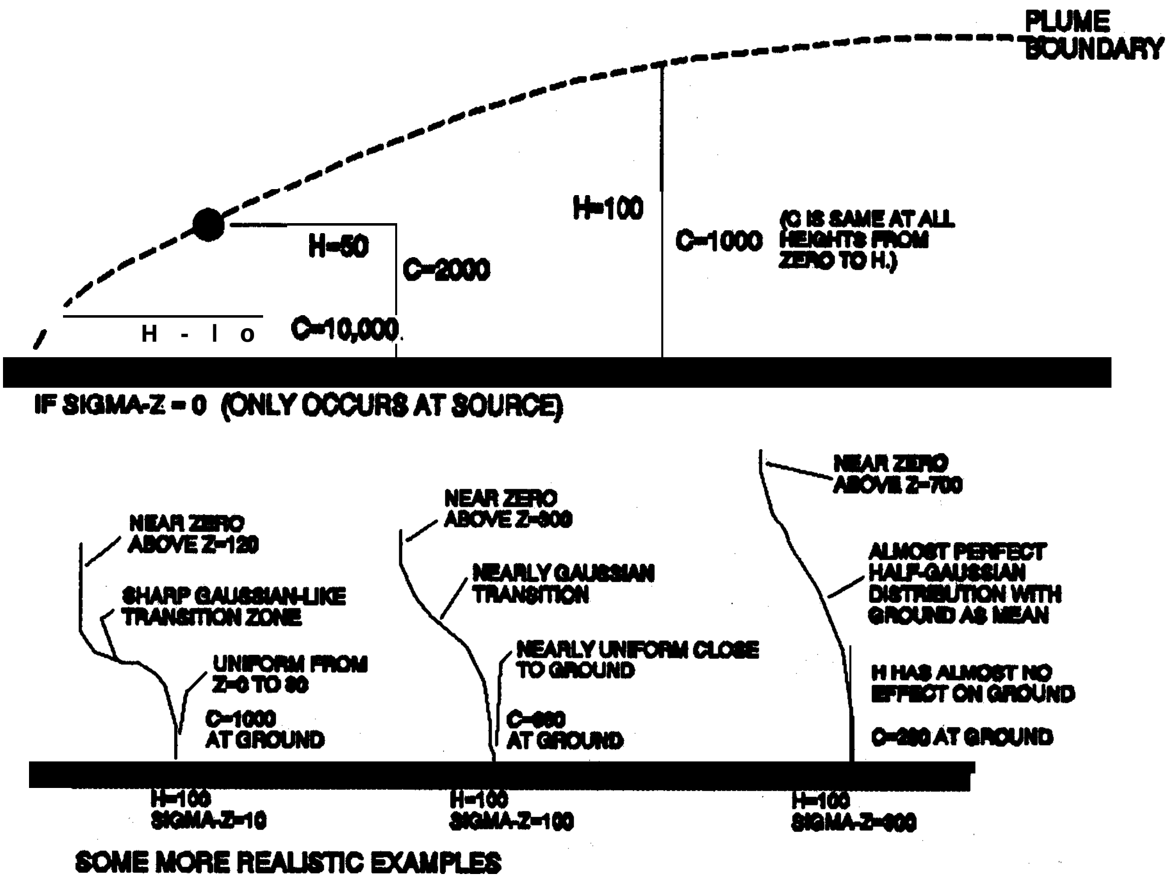


Figure 6—Effects of Gaussian dispersion on an initially uniform distribution.

VSMOKE also calculates ground-level concentrations downwind from a source specified to have an initial vertical distribution of pollutants that is uniform from the ground to the predicted plume height. These estimates are made by allowing Gaussian dispersion processes to act upon the initially vertically uniform distribution. Figure 6 illustrates the effect of Gaussian turbulence on an initially vertically uniform distribution. The top portion of the figure shows the effect of gradual plume rise, with no vertical dispersion (i.e., $\sigma_Z = 0$). However, in VSMOKE, the effect of gradual plume rise is combined with vertical mixing effects. The bottom portion of the figure shows more realistic examples, with SIGMA-Z increasing (left to right) as the plume is transported downwind. At first, with SIGMA-Z = 10 m, the uniform vertical distribution is diluted only at the top of the layer, and ground concentration, C, is relatively high at 1000 $\mu g\ m^{-3}$. Next, SIGMA-Z increases to 100 m, causing mixing to take effect over an increasing depth of the plume, which dilutes ground-level concentration to 680 $\mu g\ m^{-3}$. Finally, SIGMA-Z increases to 300 m, causing the vertical distribution to assume a "folded" Gaussian character, which dilutes C to 260 $\mu g\ m^{-3}$. The effect illustrated in figure 6 is similar to the horizontal dispersion effect depicted in figure 5, except only one "side" of the plume is allowed to disperse-the other is bounded by the ground. Not shown in figure 6, but accounted for in the VSMOKE model, is the effect of the upper mixing height boundary (shown for a simpler case in fig. 4).

To accomplish the computations required for an initially vertically uniform source, **VSMOKE** generally follows the method outlined in Lavdas **(1986).**[9] This method reexpresses the concentration equation in terms of relative concentration, **CU/Q,** then integrates with respect to Z/σ_Z, i.e., height divided by vertical dispersion coefficient. The limits of integration are defined by **Z=0** to Z=H, where H is the plume height applicable at the given downwind distance (i.e., the entire dispersion process that defmes σ_Z is applied for the complete transport distance, whether or not gradual plume rise is assumed). When equation (13) is reexpressed in terms of relative concentration and **Z** is used in place of H within the exponential factor, the following equation results:

$$\frac{CU}{Q} = \frac{\sqrt{\frac{2}{\pi}}}{(\sigma_Y \sigma_Z H)} P_Z \qquad \textbf{(17)}$$

where

P_Z is the inverse Gaussian distribution **function** in terms of Z/σ_Z.

The equation for P_Z is expressed as:

$$P_Z = \int_0^{\frac{H}{\sigma_Z}} \sqrt{\frac{1}{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{Z}{\sigma_Z}\right)^2\right] d\left(\frac{Z}{\sigma_Z}\right) \qquad \textbf{(18)}$$

where

0 and H/σ_Z are the limits of integration, and the integration is with respect to the ratio, Z/σ_Z (i.e., the ratio of height to vertical dispersion coeffkient).

Because equation (18) is the inverse Gaussian distribution in terms of the ratio, Z/σ_Z, it is completely analogous to that found with respect to P (or Y/σ_Y) within the **finite** line source relationship-equation (16).

For vertically well-mixed concentration estimates, equation (14) is reexpressed in terms of relative concentration, **CU/Q;** then, using an equivalent height, H_E, in place of A_{MIX}, the following expression is obtained:

$$\frac{CU}{Q} > \sqrt{\frac{1}{2\pi}} \frac{1}{\sigma_Y H_E} \qquad \textbf{(19)}$$

[9] **Appendix D of Lavdas 1986.**

where

H_E = an equivalent height or depth of a ground-based smoke layer in meters, with respect to ground-level concentrations, assuming vertically uniformly distributed pollutants.

Equation (18) and expression (19) are combined to calculate the effective depth of pollutants after subsequent Gaussian dispersion processes have affected the vertical distribution of an initially vertically uniform source. This yields:

$$H_E = \frac{H}{2\ P_Z} \tag{20}$$

where

H = the plume height as defined in equation (13), but now interpreted as the top of the initially vertically uniform plume layer, and P_Z is obtained from equation (18).

Like the uniform finite line source equation, equation (26.2.17) of Abramowitz and Stegun (1972) is used to evaluate P_Z. Equation (20) is used to obtain H_E, then expression (19) may be solved for concentration, yielding:

$$C = \frac{Q}{\sqrt{2\pi}\ \sigma_Y\ H_E\ U} \tag{21}$$

In all cases where concentration from a single pollution source, C, is calculated, the background concentration, C_{BKG}, is added before concentration is output to the user. For particulate matter, the calculation is straightforward: C_{BKG} is added to C, yielding the total concentration, C,, for each receptor, or:

$$C_{TOT} = C_{BKG} + c \tag{22}$$

where

C,, C_{BKG}, and C are given in micrograms per cubic meter for particulate matter.

In the case of carbon monoxide, background and total concentrations are expressed in parts per million on a mass basis. VSMOKE first determines the density (mass per unit volume) of the moist atmosphere, multiplies this value by the parts per million input for carbon monoxide to obtain a C_{BKG} density, then uses equation (22), using the calculated density of C for carbon monoxide resulting from the fire. C_{TOT} is then reexpressed as parts per million of total carbon monoxide within the atmospheric mixture.

VSMOKE Horizontal and Vertical Dispersion Coefficients

To calculate the horizontal and vertical dispersion coefficients, σ_Y and σ_Z, **VSMOKE** uses the well-known Pasquill-Gifford-Turner (P-G-T) system This system is most applicable for a ground source over open country in rural areas with smooth or gently rolling terrain. Both dispersion coefficients are specified as functions of downwind distance and atmospheric stability class. Graphs of σ_Y and σ_Z appear in many references, e.g., **Pasquill (1974),** Turner **(1970),** and Hanna and others (1982). In VSMOKB, downwind distance includes the sourceto-receptor distance and may also include virtual distances to account for "initial" Gaussian dispersion at the source site. Stability class in VSMOKB generally follows the objective scheme described by Turner (1964) and Lavdas (1986). Like many of the more recent U.S. EPA models, VSMOKB extends the Turner system to distinguish between day and night for the near neutral stability class. In VSMOKB, "near neutral - day" stability reflects an adiabatically neutral lapse rate and "near neutral - night" reflects somewhat subadiabatic conditions, i.e., an approximately isothermal lapse rate.

Formulas for calculating dispersion coefficients appear in many published Gaussian plume models. For example, in the U.S. EPA model, CDM 2.0, (Irwin and others **1985),** using the "PGSIG" option invokes the P-G-T system. The CDM 2.0, PGSIG formulas are followed in VSMOKB with one exception: the vertical dispersion coefficient for the near neutral stability class during daylight uses formulas provided by Turner.[10] The unpublished Turner formulas yield results that, at very short distances, are more consistent with those calculated for the other stability classes. While the differences are inconsequential in any individual **VSMOKE** concentration estimate, prescribed **fire** smoke management procedures often use a meteorological case sensitive structure. This structure mandates internal consistency among estimates in the design of VSMOKB. The effects of tbis consistency become apparent when virtual distance calculations are made and model runs with differing stability classes are compared-an inappropriate σ_Z value at short range could lead a land manager to modify a meteorological criterion for burning in the "wrong" direction. The Turner-based VSMOKB values for σ_Z in, "near neutral - day" conditions are slightly less than the CDM 2.0 PGSIG option values for the range of downwind distances displayed in VSMOKB output, i.e., from 0.100 to 100.0 kilometers (km). This difference causes VSMOKB concentration estimates for the "near neutral day" stability class to slightly exceed those based on CDM 2.0 PGSIG coefficients. The greatest relative difference between the two is about 11.6 percent at 0.100 km. This difference lies well within the factor of 2 range of uncertainty intrinsically associated with Gaussian plume model dispersion coefficients (Turner 1970).

The equation used to calculate horizontal dispersion coefficient, σ_Y, in VSMOKB follows:

$$\sigma_Y = 465.116\ X_{KM} \tan\left(A + B \ln X_{VYKM}\right) \qquad \textbf{(23)}$$

[10] **Personal** communication. **1975. D. B. Turner, U.S.** Environmental **Protection Agency, Research Triangle Park, NC.**

where

X_{VYKM} = downwind distance, including virtual distance due to initial horizontal dispersion, in kilometers,

465.116 = 1000 (meters to kilometers) divided by 2.15; is approximately the 0.1 amplitude point of the Gaussian distribution **function,** and

A and B **=** constants set according to stability class (table 1).

The tangent argument in brackets in equation (23) may be thought of as a nominal horizontal "spread angle" for the plume. This spread angle is that angle to the downwind centerline trajectory for which the concentration from a point source maintains a **value** 0.1 times that at the centerline. Table 2 shows that the effect of A and B within equation (23) at various downwind distances affords approximate adherence **to** the spread angles.

The vertical dispersion **coefficient,** σ_Z**,** in VSMOKE is calculated by using the following power function:

$$\sigma_Z = C\, X_{VYKM}^{\;D} \qquad \textbf{(24)}$$

where

C and D = stability class and distance **dependent** constants (table 3).

Other techniques for **determining** dispersion coefficients are widely used. Some simply use different constants and formulas to obtain stability and distance dependent **coefficients** (Hanna and others **1982**[11]**)**. Others may assume different dependencies such as substituting travel time for downwind distance. **One** theoretically appealing method (Irwin 1983) relies on wind variability statistics to help defme **the** coefficients, eliminating some of the empiricism inherent when using stability classes. Unfortunately, obtaining wind fluctuation data for routine, operational, prescribed fire applications seems unlikely in the near future.

The flexible structure of the **VSMOKE** program readily accommodates revisions using certain types of alternatives to the P-G-T system. Alternatives include the theoretically appealing use of wind fluctuations in a manner similar to Irwin's (1983). Smoke and visibility estimates are very sensitive to the estimated values of **both** dispersion **coefficients,** σ_Y and σ_Z. Careful attention must be given to the effects of any dispersion **coefficient** determination scheme on the "bottom line" ground-level concentration estimates before any revisions to **VSMOKE** are made in an operational enviromnent.

[11] **Page** 30 of Hanna and others 1982.

Initial Dispersion Coefficients and Virtual Distances in VSMOKE

In VSMOKE, specification of "initial" horizontal and vertical Gaussian dispersion coefficients accounts for any dispersing effects at the source other than those directly associated with source size and plume rise. Input by the user on a period-by-period basis, the effect of these coefficients on concentration estimates is calculated by using the "virtual source" modeling concept often used in U.S. EPA models (e.g., Wackter and Foster 1986). Virtual source modeling calculates the appropriate value of a dispersion coefficient, σ_Y or σ_Z, "as if' the source were located further upwind than its physical location. The extra downwind distance equals that needed for a point source to generate a dispersion coefficient value equal to the specified "initial" value. Figure 7 illustrates the virtual distance concept. Except for the 500-m translation, the concentration distributions in the top and bottom portions of the figure are identical. The 500 m is the downwind distance required in this illustration to attain a desired horizontal dispersion coefficient value of 30 m. That 500-m distance is added to all downwind receptors only to compute the horizontal dispersion coefficient, σ_Y.

VSMOKE virtual distances are calculated by inverting the relationships used to calculate the dispersion coefficients. The vertical dispersion coefficients are determined by simple power laws (see equation (24)); inverting them is analytically straightforward. The horizontal dispersion coefficients are calculated by a combination of trigonometric and logarithmic functions (see equation (23)) not readily inverted. To approximate the inverse of these functions, VSMOKE constructs an array of calculated horizontal dispersion coefficients for each stability class and a wide range of downwind distances. When a virtual distance is required for a specific coefficient and stability class, array references to and geometric interpolation between the two closest values are performed. This technique yields more consistent results than the approximation formulas used in most U.S. EPA Gaussian plume models, e.g. Petersen and Lavdas (1986). The improved computational accuracy can be important in some VSMOKE applications. For example, several program runs may be made to compare fires of differing size in an attempt to meet prescribed fire management criteria by reducing the size of a planned burn.

Stability Class Determination in VSMOKE

Stability class determination in VSMOKE follows the objective scheme of Turner (1964) and Lavdas (1986), based on the categorical system developed by Pasquill (1961). This system essentially consists of seven stability categories with descriptors (table 2). Like Pasquill (1974), Lavdas (1986), and many US. EPA models (e.g. Irwin and others 1985), VSMOKE distinguishes between "day" and "night" under the near neutral stability class. VSMOKE has the capability to either accept input values for stability class and a day/night flag or calculate stability class and day vs. night from input location, date, time, and surface weather parameters. Turner's (1964) calculation procedure is followed with one additional step. Ephemeris determination of day or night is based on time of sunrise and sunset according to procedures in the U.S. EPA meteorological pre-processor program, RAMMET, as given by Catalano (1987). These sunrise and sunset times differ sligbtly from those published in almanacs, partly because RAMMET uses a single standard year in some of its ephemeris equations and partly because almanac

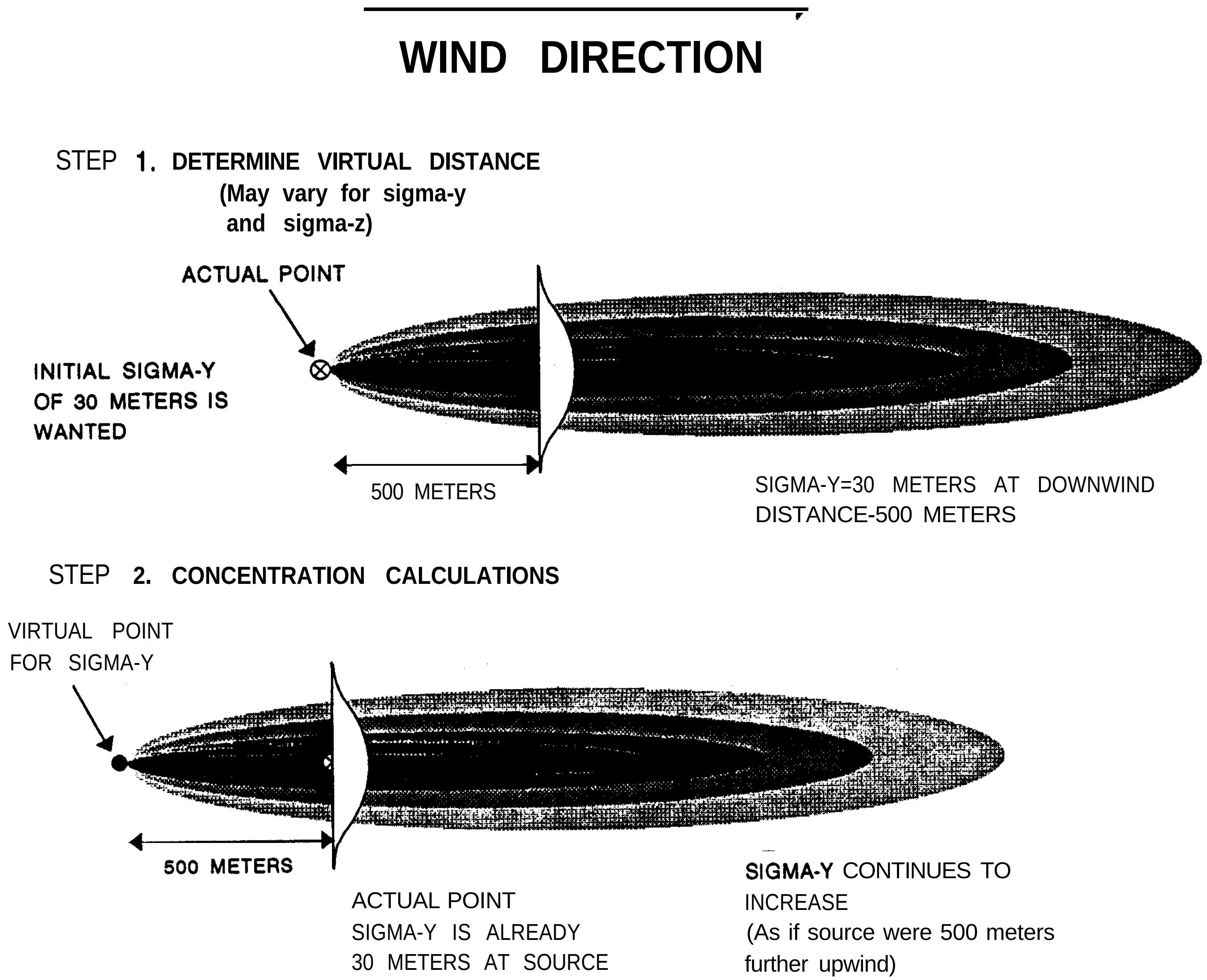


Figure **7—Virtual** distance concept (pint source illustrated).

calculations account for **refraction** and the radius of the solar disk. **RAMMET** assumes no refraction and neglects the solar disk radius. With implementation details dependent on the specified interval between analysis periods, VSMOKE, also follows the **RAMMET** criterion that restricts changes in stability class to no more than one category per hour.

Users with meteorological backgrounds may choose to use National Weather Service upper air and surface observations to help specify stability class. These users should note the findings of Lavdas (198 1) for the early morning (1200 UTC) soundings at Medford, OR. The extremely stable and moderately stable classes averaged a lapse rate of about 0.035 kelvin **(K)** per m near the ground; the slightly stable class averaged about 0.020 **K** per m. Both these values equal those specified by U.S. EPA (e.g., Catalano 1987) in plume rise calculations. The near neutral class at night averaged about 0.010 K per m, which is close to isothermal. Because the Lavdas findings and the U.S. EPA stable class lapse rate values agree, the practice of basing stability class at night on observed lapse rate is credible. Moreover, the day vs. night "adiabatic" and "subadiabatic" distinction made in VSMOKE within the near neutral stability class reflects the distinction made by Pasquill(1974). Therefore, an isothermal layer at the surface layer of the atmosphere would tend to dictate the near neutral night class, while an adiabatic lower atmosphere would tend to dictate the near neutral day class regardless of time of day.

Attempts to distinguish among the various daylight stability classes by using near surface lapse rate have not been notably successful. Atmospheric turbulence in near neutral or unstable conditions tends to efficiently force the vertical temperature gradient to a value very close to a neutral lapse rate. How unstable a lapse rate the atmosphere can sustain seems to be tied more closely to surface heating and frictional characteristics than to the intensity of turbulence. This circumstance limits using the degree of instability of the vertical potential temperature profile to specify Gaussian dispersion coefficients.

VSMOKE Smoke Receptors

VSMOKE concentration estimates are made along the centerline of the plume trajectory from the fire at ground level. In atmospheric modeling terminology, VSMOKE uses a Lagrangian (i.e., airborne particle following) modeling approach. Concentration estimates are made at logarithmically spaced distances ranging from 0.100 to 100.000 km (or about **1/16** to just over 60 miles). Logarithmic spacing causes the receptors to be closest to each other near the fire, where variations in smoke effects are greatest. An interval of a factor of about 1.2589 **($10^{0.1}$)** is used. For sources with no plume rise, this spacing keeps the decrease in concentrations from a fire between adjacent receptors to just under a factor of 2. More rapid increases of concentration are possible with increasing distance when a smoke plume from a fire with nearly complete plume rise first intercepts the ground. The receptor spacing is dense enough to allow sufficiently accurate geometric interpolation of concentration estimates to intermediate distances. All smoke concentration estimates given by VSMOKE include specified constant background values for each period; thus, relative changes in the output concentration values are generally **less** than those cited for concentrations solely from the source.

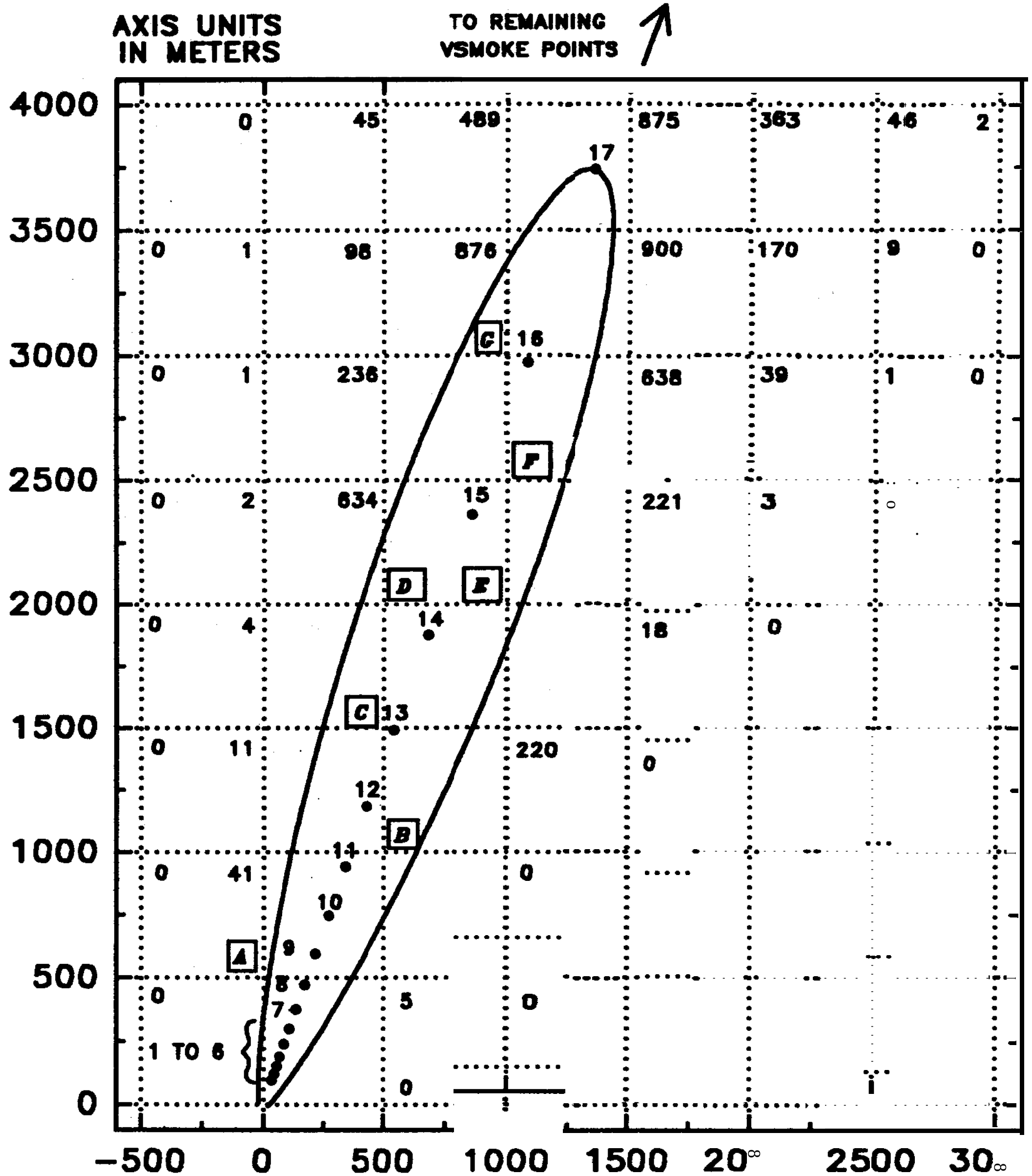
The **VSMOKE** plume centerline approach uses receptors located along the plume trajectory. By using the uniform flow assumption **from** Gaussian plume models **(Hanna** and others 1982) and aligning all receptors directly on the plume centerline, VSMOKE removes all mathematical reference to wind diction **from** the concentration equations. By removing wind direction dependency **from** its calculations, VSMOKE in effect employs concentric rings about the smoke source as receptors. Therefore, no explicit plume pathway exists in VSMOKE. Instead, the model provides concentration estimates along the trajectory without attempting to spatially locate that trajectory, except by downwind distance **from** the emissions source. In this sense, VSMOKE may be regarded as a onedimensional model.

The VSMOKE methodology that locates all receptors along the downwind centerline plume transport trajectory (SFFLP 1976) represents a significant point of departure **from** many U.S. EPA dispersion models. The receptor methodology more closely resembles the older U.S. EPA PTDIS model than any of the recommended air quality models in the "Guideline to Air Quality Models" (U.S. EPA **1986, 1987).** However, the PLWUE II model (Seigneur and others 1984) listed in the EPA Guideline is a specialized model that uses downwind distance to define receptor locations.

Models that rely on fixed point receptors are subject to large errors in smoke concentration estimates caused by errors in wind flow specification. These errors are associated with small displacements of relatively narrow smoke plumes, and are more likely to occur in the stable conditions characteristic of nocturnal light and variable/drainage wind regimes. These conditions are associated with high smoke and visibility hazard. In these cases, the model plume is narrow and the uncertainty in the wind field is high. By using a "plume following" technique that assures the targeting of every receptor by the smoke plume, VSMOKE avoids much of the error that "fixed point receptor" models are prone to.

VSMOKE is oriented toward short-term hazard avoidance near or in any direction downwind of a fire-generally an episodic event. Many U.S. EPA models using fixed receptors estimate average impact at a point or over a geographic area during a period of time when a variety of weather regimes may occur (Irwin and others 1985).

Figure 8 illustrates the differences between the VSMOKE plume centerline and EPA fixed point receptor modeling approaches. This figure shows the effect of a smoke source upon a hypothetically "clean" background. To compute the concentration values in the figure, a 1,000 gram per second smoke emission rate with no accompanying heat emission rate, a slightly unstable atmospheric environment, a 4 ms^{-1} transport windspeed, and a 1,500-m mixing height are assumed. Initial horizontal and vertical dispersion coefficients of 5 m each are also assumed. The figure shows the 1,000 $\mu g\ m^{-3}$ concentration isopleth resulting from a wind direction of **200°.** The resulting locations of the first 17 (total 3 1)



CENTERLINE POINTS#	CONCENTRATION
1	405,530
2	302,592
3	221,466
4	159,308
5	112,863
6	78,914
7	54,563
8	37,374
9	25,402
10	17,156
11	11,528
12	7,714
13	5,145
14	3,423
15	2,273
16	1,508
17	999
ETC.	ETC.

GRID POINTS	CONCENTRATION	REMARKS
A	360	Plume missed all nearby points (1/100 of centerline value)
B	5,282	A "near" hit (1/2 of centerline)
C	4,985	A "lucky" hit (Almost full centerline)
D	1,850	Two near hits (About 1/2 centerline)
E	1,404	
F	,904	Direct hit
G	1,445	Almost a direct hit

Figure 8—VSMOKE centerline vs. Fixed grid point receptor. The grid cannot reliably "find" the plume until it is wider than the grid spacing. The outline shows the isopleth for a concentration value of 1,000.

VSMOKE receptors is shown along the plume centerline. “Receptor 17,” at a downwind distance of 3,981 m (just under 2.5 miles), is nearly touching the isopleth, as would be expected from its tabular concentration value of 999 $\mu g\ m^{-3}$. The VSMOKE receptors “capture” the extremely high smoke concentrations close to the smoke source, with the highest tabular concentration exceeding 405,000 $\mu g\ m^{-3}$.

Figure 8 also illustrates smoke concentration values as they would be determined from a cartesian grid of receptors with a spacing of 500 m, a north-south, east-west orientation, and the zero point of the grid assigned to the central smoke source location. Where the grid points fall well outside the 1,000 $\mu g\ m^{-3}$ isopleth boundary, concentration values are shown near the applicable grid point location. Note that the grid of receptors is insufficiently dense to capture the very high concentrations characteristic of the values given for the first 10 to 12 VSMOKE receptors.

The first labeled grid point, A, is 500 m north of the source and very close (within 20 m) to the 1,000 $\mu g\ m^{-3}$ isopleth, yet its concentration value is only 360, or less than 1 percent of the centerline value for its downwind distance from the source. The plume almost completely misses point A's “sister receptor” 500 m to its east. On the other hand, point B (1,000 m north and 500 m east of the source) scores a “near hit”; its concentration value of 5,282 $\mu g\ m^{-3}$ is almost one-half the value for a receptor directly on the centerline at its downwind distance. However, point B’s “sister receptors” 500 m to the west and to the east give little or no hint of the magnitude of the plume’s impact 1 km north of the source. A “lucky hit” is scored at point C, which is only about 43 m from the plume’ centerline while nearly 1,600 m distant. The distance from the centerline of point C is only about 0.27 times the value of σ_Y for its downwind distance, which means that it captures about 0.964 of the centerline concentration at its downwind distance. Point C’s concentration value of 4,985 $\mu g\ m^{-3}$ is close to the value for the nearby VSMOKE receptor 13 value of 5,145 $\mu g\ m^{-3}$. However, if the plume isopleth undergoes a small rotation in either direction, detection of the maximum impact of the plume 1,500 m north of the source is primarily a matter of luck. This assertion is supported by the much lower concentration values 500 m to the east and west of point C.

Plume detection becomes more reliable as distances from the source increase. Adjacent points D and E bothscore near hits, and given the low concentration values to the east and west of these points, some indication of the shape and magnitude of the plume at this distance begins to emerge. At increasing distances, points F and G score nearly direct hits and are surrounded by significantly high gridded concentration values. Along the two northernmost rows of gridded receptors (3,500 m and 4,000 m north of the source) the Gaussian shape of the plume becomes quite obvious. At this distance, the VSMOKE receptor spacing has increased so that its adjacent receptors are farther apart than the gridded receptors. Centerline concentration values at such downwind distances from the source change slowly enough to allow continuous increases in VSMOKE receptor spacing.

To produce reasonably accurate averaged concentration estimates, models with geometrically fixed receptors are dependent on a very accurate averaged representation of plume widths, orientations, and locations over the period of simulation. Narrow plume models **cannot** be expected to produce reliable short-term concentration estimates at fixed locations in an episodically oriented operational environment. For example, in moderately stable conditions, a **VSMOKE-like** model with fixed receptor locations must specify the effective plume transport direction within **5°** or less (table 2) in order to maintain **factor-of-**10 accuracy! Fox (1981) also points out that errors of representativeness and variability associated with applying a single wind direction for the effective area between source and receptor tend to be large compared to the characteristic angular dimensions of the pollutant plume. This leads to large errors in estimates of short-term single source impacts at fixed locations.

In "real-world terms," the relatively large uncertainty in the direction of plume transport compared to its width means that a fixed-point receptor model is apt to depict a plume trajectory showing a given receptor to be free of smoke, when a small change in wind direction could have a heavy impact on that same receptor. The VSMOKE approach eliminates much of the sensitivity of Gaussian plume models to small errors in the specified horizontal direction of pollutant transport. Such errors can have a crucial effect on the analysis of an episodic and potentially hazardous event such as smoke intrusion from a ground fire over a sensitive location.

Expected Accuracy of VSMOKE Concentration Estimates

The accuracy of VSMOKE concentration estimates is inherently limited by the scope of the dispersion model. Uniform steady-state fire, smoke and heat emissions, and meteorological conditions are assumed over the portions of the atmosphere containing smoke during the course of any single analysis period. Variations in dispersion rate and wind flow minor enough to retain a generally intact and uniform smoke plume are accommodated by this modeling approach, with minimal error introduced in the smoke concentration estimates for points centrally located within the plume. However, significant variations in important meteorological parameters, particularly in the wind field, will seriously degrade model performance. Major complexities in wind flow, such as a wind field that causes the smoke plume to double back on itself, are completely beyond the model's scope.

The accuracy of VSMOKE smoke concentration estimates is **affected** by the accuracy of the emissions data supplied to the VSMOKE dispersion model. Any error in a pollutant emission rate will result in a 1: 1 proportionate error in the resulting smoke concentration estimate (equations 13 to 21). Concentration estimates near a fire are also extremely sensitive to plume rise assumptions both within the model and as input. Smoke concentrations at the ground increase rapidly as an elevated plume first intercepts ground-level receptors. Therefore, a relatively small decrease in plume rise can result in a large increase in the estimated concentration at a given downwind distance. This sensitivity is most marked if the user input indicates that all or nearly all smoke attains **full** plume height. Similarly, if the proportion of smoke subject to plume rise is incorrectly specified, large errors in smoke concentration estimates can result, particularly near the source. For example, if input indicates that 99 percent of smoke undergoes significant plume rise, but only 80 percent actually does so, the resulting smoke concentration estimates close to a fire can be too low by a factor of 20.

VSMOKE! concentration estimates are also highly dependent on the various meteorological input values supplied to the dispersion model. For example, if plume rise does not change, concentration estimates are inversely proportional to the transport **windspeed;** halving the windspeed doubles the concentration estimates. However, transport windspeed also influences estimated plume height; in unstable or near neutral-day conditions, doubling the transport windspeed halves the plume rise. In stable conditions (or near neutral at night, when an isothermal atmosphere is assumed by **VSMOKE),** an eightfold increase in transport windspeed is generally required to halve the plume rise. Any change in the input or calculated stability class value can also result in a large change in smoke concentration estimates.

In part, this sensitivity is a consequence of the categorical nature of atmospheric stability as used in VSMOKE. In the categorical system, a small change in an input value that specifies or influences stability class can cause a rather large step change in estimated concentrations. For a fire with no significant plume rise, a more stable class results in higher ground-level centerline concentration estimates. For a fire with all or nearly all smoke attaining a significant plume rise, a more stable class may sharply reduce VSMOKE concentration estimates for nearby receptors-the higher concentrations remain above the ground. Mixing height usually exerts less influence on ground-level concentration estimates close to the fire than the other major meteorological parameters. However, once the plume is well mixed within the mixing layer, which occurs at longer distances and in more unstable conditions, halving mixing height can double concentration estimates.

Internal calculations within the Gaussian plume dispersion model are affected by the VSMOKE assumption that uniform "steady-state" conditions prevail during any given period. When all the variables affecting smoke concentrations downwind have been determined, they are **fixed** in time and space for the full period and over the full geometric domain from smoke generation to any downwind point. Although VSMOKE can generate smoke concentration estimates for several sequential periods, the dispersion model calculations for each period are considered independently.

The empirical modeling techniques used in VSMOKE to specify dispersion coefficients are far from exact but, according to Turner **(1970),** can give acceptable concentration estimates. Given a perfect specification of plume rise (which is easiest to obtain when little or no plume rise occurs during smoldering conditions), the accuracy of the pollutant concentration estimates due to the source is completely dependent on the accuracy of the dispersion coefficients and the validity of the Gaussian plume assumption. The expected accuracy of the

Gaussian plume dispersion model is greatest closest to the pollution source. At the closest distances, estimates of the vertical dispersion coefficient may lie within a "factor of 2," and the combined effect of errors in the vertical and horizontal coefficients may result in estimates remaining within a "factor of 3" of actual values. Therefore, concentration estimates within 1 km (about 5/8 mile) of a perfectly specified smoldering burn site may fall within a factor of 3 of actual values. The expected accuracy of the dispersion model becomes much worse with increasing distance, especially beyond 10 km (about 6 miles) from the source. Pasquill(l974) characterizes the accuracy of the dispersion coefficients at such distances as "speculative." VSMOKE estimates at long distances might best be regarded as little more than hypotheses agreed to by experts in the absence of better information.

The VSMOKE Lagrangian receptor location approach, in a sense, gives the model a measure of accuracy not possible in an equivalent Eulerian ("fixed grid") receptor model. An Eulerian model estimates that a smoke concentration, C_E, will occur at a specific receptor point, (x,y), while VSMOICE only warns that a smoke concentration, C_L, will occur at a downwind distance, X, from the fire. The location of occurrence of C_L is not specified except by downwind distance from the fire; in VSMOKE that distance could be in any direction from the fire.

Because VSMOKE does not locate the smoke trajectory, it must be independently determined. Not only the width of the plume, but uncertainties in smoke transport directions should be considered when determining areas of possible smoke impact. The user must allow for the variability and uncertainty always associated with the wind field, and the risk associated with an imperfect weather forecast. Variations in wind are nearly always present both in space and time. Winds aloft may transport smoke in directions not anticipated based on surface winds alone. Those experienced in prescribed fire know how much wind can vary within a burn site as well as during the course of a burn. For smoke, wind variations literally above and beyond the burn site are also crucial to prescribed burning decisions.

When using VSMOKE smoke concentration estimates it is best to assume that the estimated concentrations will occur over a rather wide arc to either side of the nominal downwind direction. SFFLP (1976) recommends using a 30° angle to either side of an observed representative downwind direction. At least 45° to either side is required when a forecast downwind direction is used. National Weather Service public forecasts of wind do not specify direction more precisely than by 8 compass points. When no consistent wind direction exists (e.g., near calm, light and variable, or stronger but highly variable winds), concentric circles about the fire site may be the only reasonable basis for setting geometrically based criteria for smoke management decisions. A preliminary study of wind direction persistence and forecast accuracy (Lavdas 1993) indicates that the possible effect of smoke in all directions should be considered, regardless of the meteorological regime.

Crossplume Sightline Characteristics

The VSMOKE! Crossplume Sightline Characteristics Model

VSMOKE can estimate plume visibility and contrast ratio along crossplume sightlines at ground level centered along the downwind plume trajectory. The two parameters, visibility and contrast ratio, are closely related. Visibility defines how far one can see a "target" with a given clarity. Contrast ratio defines the clarity with which one sees a target at a given distance. Because the atmosphere acts to scatter and absorb light (a propensity greatly increased by impurities such as smoke), clarity decreases as distance increases. In other words, as distance increases along a sightline, contrast ratio decreases. The visibility along a sightline is the length at which the contrast ratio falls to a critical value.

The sightline estimates of visibility and contrast ratio are based on relationships that are valid only in dry conditions, i.e., when relative humidity is less than 70 percent. Like smoke concentration estimates, the sightline estimates are given as a function of downwind distance. Although it uses less computer code than the dispersion model, the sightline analysis is the most computationally intensive and time-consuming VSMOKE component during program execution. For this reason, sightline estimates are optional.

Sightline estimates are calculated from the specified background particulate matter concentration value and from various smoke plume characteristics at each downwind distance. The sightlines are constructed in short piecewise segments (along which plume characteristics are assumed to be constant) at ground level outward from and horizontally perpendicular to the plume centerline. Sightlines start with a central segment for which the centerline particulate matter concentration estimate is assumed to apply. Segment pairs are then added as required to each end of the sightline, extending until the contrast ratio drops to the specified criterion threshold value and the sightline reaches a length matching the specified visibility criterion.

The following equation for contrast ratio, adapted from Middleton's (1968) equation (4.25), is used in all VSMOKE! crossplume sightline calculations:

$$CR_a = CR_i \exp\left(-B_{EXT}\, X_{SIGHT}\right) \tag{25}$$

where

CR_a = Apparent contrast ratio (i.e., as seen along the sightline) of an object versus its background (unitless),

CR_i = Intrinsic contrast ratio (i.e., without any light attenuation) of an object versus its background (unitless),

B_{EXT} = Light extinction coefficient of the atmosphere including the effects of any pollutants in units of inverse meters, and

X_{SIGHT} = Sightline length in meters.

Light extinction characteristics are expressed through the equation (25) variable, B_{EXT}. B_{EXT} is determined by a relationship given by Tangren (1982) and later modified by Tangren in 1985. In VSMOKE, the Tangren equation for B_{EXT} applies to both smoke and background particulate matter. It is further assumed that this equation accounts for all attenuation of light (e.g., effects due to nitric oxides, NO,, are neglected). The relationship as used in VSMOKE may be expressed as follows:

$$B_{EXT} = 0.000015 + X_{PM}/300{,}000 \tag{26}$$

where

X_{PM} = particulate matter concentration in micrograms per cubic meter.

Equation (25) is valid if the light extinction coefficient, B_{EXT}, from equation (26) is regarded as constant for the full length of the sightline. Sightline segments along which the concentrations vary only minimally are used in VSMOKE. The construction of the sightline begins outward from the centerline for a crossplume distance for which the concentration is approximately equal to the centerline value already calculated by the VSMOKE model. For a point source or a relatively short line source, this central segment is set to a length 0.2 times the horizontal dispersion coefficient, σ_Y. The variation of concentration along this line segment is less than 0.005 times the centerline value. For line sources much longer than σ_Y, plume concentrations can be nearly constant for distances much longer than 0.2 times σ_Y. If the effective source line length E_{LINE}, is more than 10.3 times σ_Y, a central sightline segment of length $[(E_{LINE}/\sigma_Y) + 10.1]$ times σ_Y is used. To continue the computations of light attenuation in the plume to either horizontal crosswind side of the central plume segment, segments of length 0.1 times σ_Y are added as needed. The "off-centerline" concentration at the midpoint of each line segment is used in equation (26) to calculate the appropriate value of B_{EXT} for equation (25). In the Gaussian plume model (figs. 4, 6, and 8), concentration values continuously decrease with increasing distance from the plume centerline. If light attenuation calculations are required once the off-centerline crossplume distance has reached the absolute value of 5.0 times σ_Y plus one half of E_{LINE}, no additional "in plume" calculations are made. At these large crossplume distances, the effect of the smoke plume is considered negligible and the background concentration value is used in equation (26).

The following methodology applies to these sightline calculations. X_{PM} in equation (26) for the central sightline segment is the sum of the centerline particulate matter concentration resulting from the fire and the input background value. B_{EXT} for the central segment and an assumed CR, of 1 (i.e., perfect white against perfect black) are used in equation (25) to obtain CR_a for the central segment. If CR_a is higher than the user criterion, then visibility is longer than the central segment, and more contrast ratio calculations are required to obtain a visibility estimate. If the segment is shorter than the visibility criterion, more contrast ratio calculations are required. In either case, as calculations continue, the central segment CR, becomes the new CR, for the next CR, calculation. In addition to the effects of the central segment, this CR_a includes the effects of the two sightline segments adjacent to both ends of the centerline segment. A new **value** of X_{PM} at the representative crossplume distance for the two new sightline segments is used to determine B_{EXT} for the new segments only. New segments are added to both ends of the sightline until the input criteria for both contrast ratio and visibility are attained. For each new segment pair, the CR, of the last complete **sightline** calculated becomes the CR_i with respect to the new segment pair. When the sightline segments reach the criterion crossplume distance, plume calculations are terminated. If the sightline must be extended further, the background concentration as X_{PM} in equation (26) and the resulting **value** of B_{EXT} (equation 25) are used. The final visibility estimate corresponds to the total sightliue length for which the user-specified contrast ratio criterion can just be maintained. The fmal contrast ratio estimate applies to a completely constructed sightline with a total length equal to the user-specified visibility criterion.

Visibility calculations during sightline construction are performed from a modified equation (25):

$$V = \ln (CR_i/CR_a)/B_{EXT} \qquad \textbf{(27)}$$

where

V = visibility in meters.

Figure 9 illustrates the construction of sightlines for an ideal case. Within 300 m of the source and near the smoke plume centerline, visibility is near zero and does not register on the graph. At 450 m, a short sightline is shown in the "east-west" horizontal crossplume direction. Visibility conditions improve and the sightline extends outward to greater distances as downwind distance increases. At 1,050 m north of the **plume,** the plume "boundaries" are **almost** reached. At 1,200 m, "sightline **breakthrough"** is achieved and an individual to one side of the plume can just see completely through the plume and distinguish objects at the far side of the plume. As the effect of the plume on visibility continues to decrease with **increasing** downwind distance, one may see objects at the far side of the plume with increasing clarity, and the ultimate crossplume visibility continues to increase.

VSMOKE crossplume visibility estimates sometimes exhibit an abrupt increase with respect to downwind distance near the sightline "breakthrough" zone (fig. 9). This sudden increase occurs when a sightline is constructed through a dense smoke plume of limited **crossplume** extent within a much clearer background atmosphere. At a given downwind distance, the contrast ratio may be reduced to just below the criterion **value** within the smoke plume-which yields a low visibility estimate. At the next greater downwind distance, the sightliue "just breaks through" into the clear atmosphere. According to the input contrast ratio criterion, the visibility is much greater, but the visual quality of objects within the clear atmosphere seen through the plume will barely meet the contrast ratio criterion. The change in the contrast ratio estimates in this "sightline breakthrough zone" is usually far less

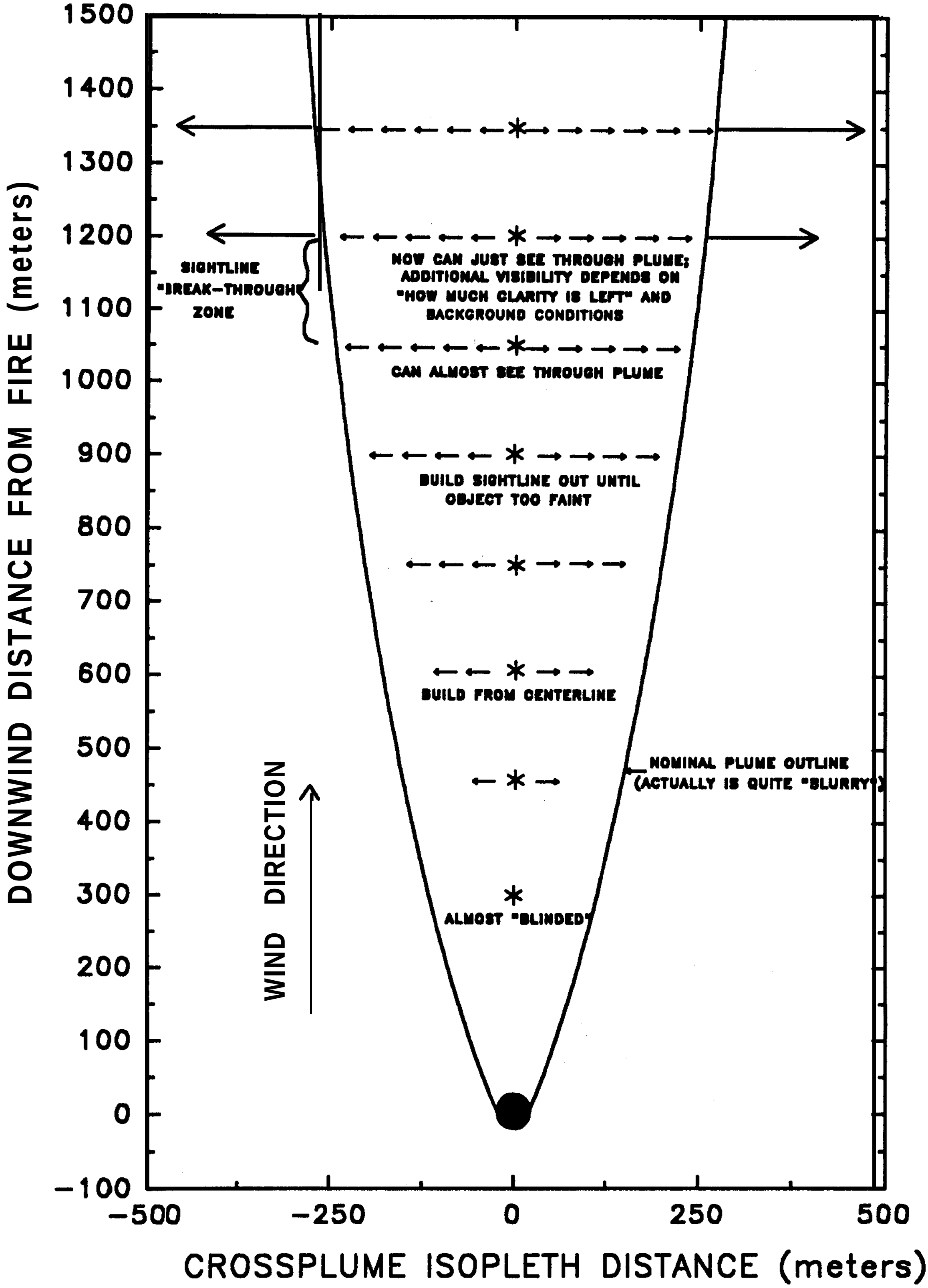


Figure 9—C struction of horizontal crossplume sightlines MOKE.

drastic. In these cases, the contrast ratio estimates may give a clearer picture of the plume's overall visual characteristics and its potential to contribute to a roadway hazard.

Figure 10 illustrates the behavior of **VSMOKE** estimates near the "sightline breakthrough zone." A plume 400 m (¼ mile) wide at 1,050 m downwind is set against a very clear background. The sightline using a 0.02 contrast ratio criterion is just short of break&rough. The computed visibility is about ¼ mile, and the contrast ratio for a ¼ mile sightline is perhaps 0.19. At a somewhat greater downwind distance (1,350 m), sightline breakthrough is achieved. Perhaps the contrast ratio for a ¼ mile crossplume sightline central to the plume is still only 0.25. However, because the background visibility is so good the contrast ratio does not drop to 0.20 until a sightline 10 miles long is constructed. The lo-mile visibility estimate seems to indicate good seeing conditions, but the marginally acceptable contrast ratio estimate of 0.25 is a much better indicator of the potential for visibility hazard. In this case, a person with slightly impaired vision that still meets driver's licensing requirements might not be able to see ¼ mile across the central portion of the plume.

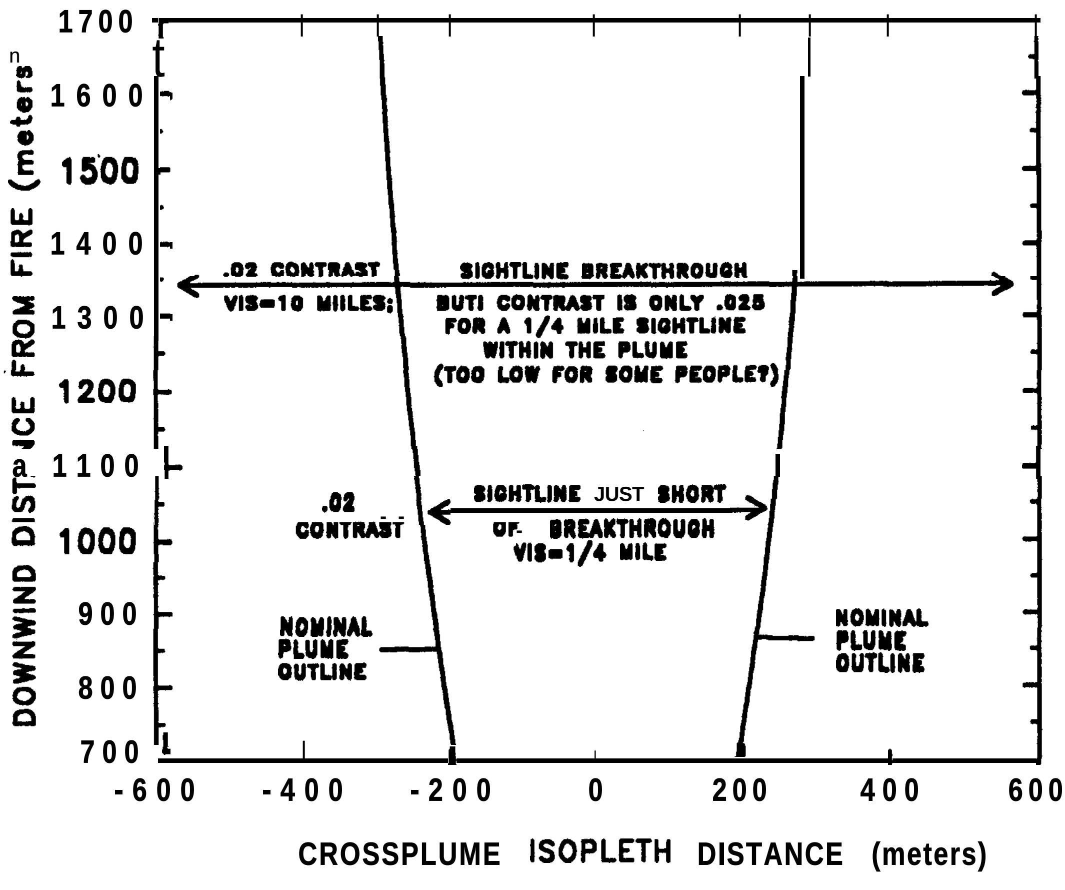


Figure **10—Sightline** breakthrough **zone** behavior with **very clear** background in **VSMOKE.**

Sightline Modeling Concerns

The modeling of sightline characteristics is subject to more problematic assumptions, uncertainties, and potential difficulties in application than any other aspect of VSMOKE. However, sightline-related estimates are included in VSMOKE, because available scientific knowledge must be used to characterize a smoke-related phenomenon that is potentially hazardous to the general public. Nevertheless, concerns associated with the use of VSMOKE sightline estimates do exist.

The greatest potential for smoke-related visibility hazard exists when relative humidity is high. Unfortunately, methodology has not been developed for making reliable predictive quantitative estimates of visibility in smoke under conditions of high relative humidity. Accordingly, sightline characteristics are not quantified when relative humidity equals or exceeds 70 percent. Sightline estimates in VSMOKE are valid only for lower humidities. These values are accompanied by asterisks when the specified relative humidity is $\geq$ 70 percent. Because sightline characteristics are likely to be **much worse** than a VSMOKE estimate when relative humidity is too high, extreme caution is absolutely necessary when interpreting any sightline value accompanied by an asterisk. A description of a **risk** index that characterizes roadway hazard caused by low visibility in high as well as in lower humidities is described in **Low Visibility Occurrence Risk Index**.

More research is needed on the appropriate input criteria for critical contrast ratio and visibility criterion for public roadway safety. A contrast ratio of 0.02 (Middleton 1968) has often been used to define runway visual range, because this value has been found necessary for an aircraft pilot to make a positive identification of a target. A somewhat higher value may be needed for roadway safety because legally operating motorists do not necessarily have the visual acuity required of aircraft pilots, Factors associated with driver and vehicle response, such as reaction time and stopping distance, should be considered when choosing a critical value for visibility. These factors vary significantly among drivers and among vehicles and are also affected by the nature of the roadway, traffic patterns, and other driving conditions. In any case, 500 feet (0.0947 miles) appears to be an absolute minimum visibility requirement for safe use of public roadways. Indeed, a much higher value can be justified for maintaining safety on many roads, particularly heavily traveled expressways such as long interstate downgrades used by many tandem trailers.

Another area of concern is that the light scattering equation (26) applies for a narrower range of conditions than those for which VSMOKE, overall, is designed. The relationship between optical properties of smoke and particulate matter concentration varies considerably from that given by equation (26). Background pollutants may not share the optical properties of smoke. Optical properties of smoke and background are subject to drastic change as relative humidity increases, and non-hydrophobic particles will scatter and absorb more light as humidity approaches saturation. In addition, visibility observations in high humidity exhibit a great deal of variation. Because the causes of these variations are incompletely understood and difficult to specify in an operational environment, the processes have not been included in this version of VSMOKE. Further discussion on the limits and the extension of the light scattering equation are given within the VSDRYG and BEXTFS subprograms of the VSMOKE computer code.

VSMOKE sightline estimates are given for the horizontal crossplume direction only; sightline characteristics in other directions may vary significantly (fig. 11). Because sightline quality can vary with respect to orientation, VSMOKE includes a calculation of a constant X_{PM} value, CRITPM, that would result in a sightline that just meets the contrast ratio and visibility criteria. Any particulate matter concentration greater than CRITPM has the potential to result in ground-level sightlines oriented in another horizontal direction from the crossplume and not meeting the input sightline criteria. Meeting the criteria depends on X_{PM} values along a particular sightline direction. For example, if centerline X_{PM} values drop very slowly as downwind distance increases and the plume is very narrow, an upwind-downwind sightline may fail to meet the criteria at a downwind distance for which the crossplume sightline does meet the criteria. To adopt a conservative approach to this problem, the user can consider any downwind distance with particulate matter concentrations greater than CRITPM as a distance that has a potential roadway safety problem.

It is uncertain whether all visual cues necessary for safe driving are adequately accounted for by the VSMOKE crossplume sightline model. VSMOKE visibility and contrast ratio estimates should be interpreted very cautiously. Such estimates are far from “proof’ that safe driving conditions are assured at a given distance from a fire. A safer, conservative approach would regard VSMOKE estimates as indicators of potential smoke-related low visibility problems at a given distance from a prescribed burn site.

Dispersion Index

VSMOKE provides an estimate of the atmospheric capacity to disperse smoke emissions from prescribed burning activity over a given area to acceptably low average concentrations downwind of that activity. The Dispersion Index (DI), developed by Lavdas (1986), is used to provide this estimate. Dispersion Index combines the effects of transport windspeed, stability class, and mixing height on smoke concentrations from areawide forestry-prescribed burning. This index is closely related to ventilation factor (i.e., the product of transport windspeed times mixing height), a parameter widely used in making operational prescribed-fire smoke management decisions. Accounting for the rate of dispersion within the mixing layer by analyzing vertical dispersion coefficients as specified by stability class, DI provides a more complete description of atmospheric dispersion than ventilation factor. Because stability class is used, DI can be determined in stable conditions when mixing height and ventilation factor are undefined. Therefore, DI provides values that can be directly compared between daytime and nighttime conditions, while ventilation factor cannot. This capability is particularly important when dealing with roadway safety problems associated with smoldering smoke sources in high humidity conditions typical of most nights in the Eastern United States.

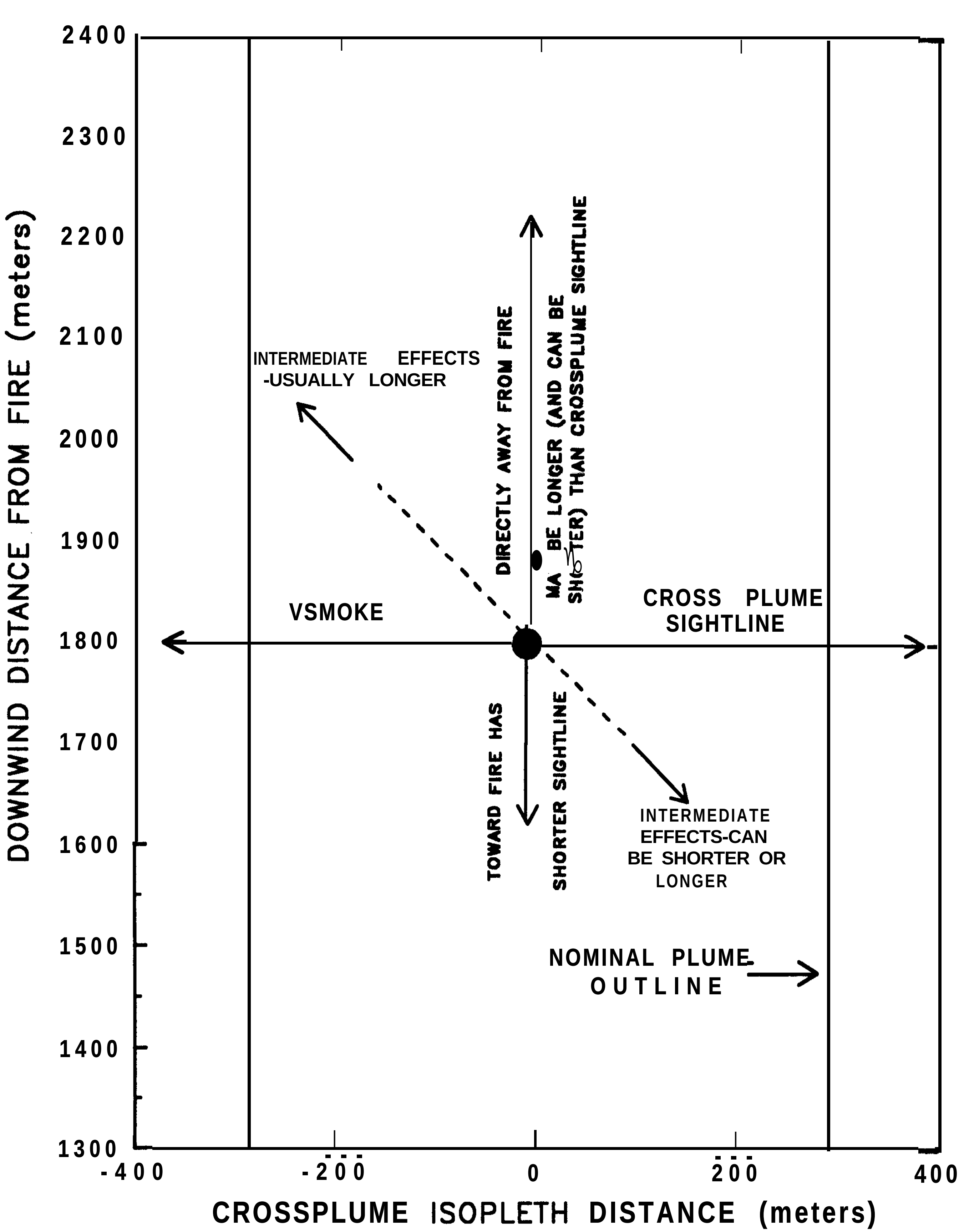


Figure 1 l-Some sightline effects for directions not treated in VSMOKE.

Dispersion Index is mathematically derived directly from widely used U.S. EPA dispersion models and measured or inferred characteristics of plume rise from prescribed fires of low to moderate intensity. A uniform area emission source representing the aggregate effects of prescribed-fire activity as typically conducted in the Eastern United States is used within an adaptation of the U.S. EPA climatological dispersion model (Busse and Zimmerman 1973). The prescribed-fire activity source occupies a 50 by 50 km^2 area (approximately 1,000 square miles), and the adapted dispersion model calculates smoke concentration for an "impact analysis point" at the downwind edge of the area (fig. 12). The model allocates prescribed-fire smoke evenly between substantial plume rise and very limited plume rise. The plume rise smoke is assumed to be well mixed within its "effective depth." This uniform mixing is a result of vertical dispersion processes and the aggregate effect of a number of burns of varying intensity assumed to be occurring within the area. The effective depth corresponds to the mixing height if the atmosphere is unstable or near neutral. If the atmosphere is stable, effective depth is determined from characteristic prescribed-fire heat emission rates and representative atmospheric conditions. The remaining smoke with very limited

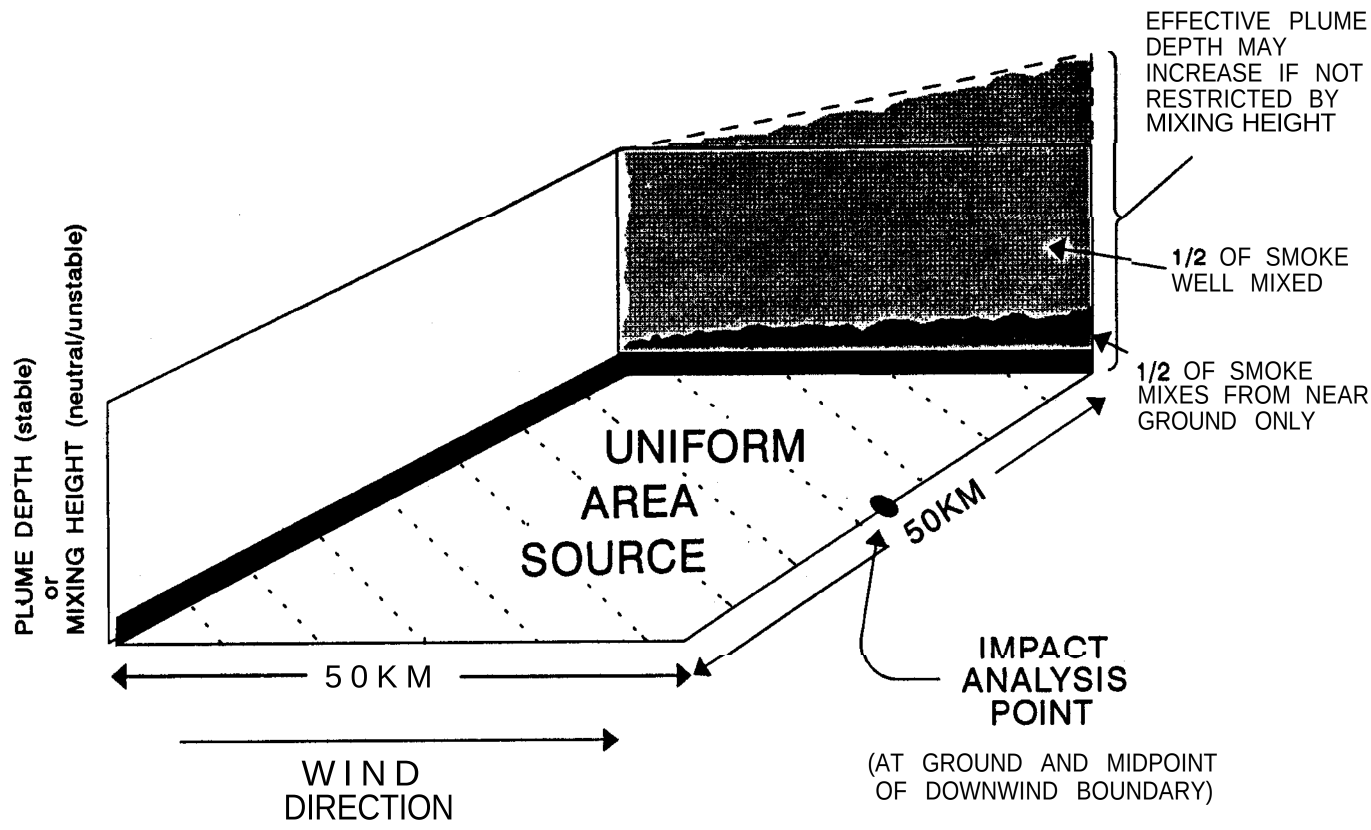


Figure 12-Dispersion index emissions model as used in VSMOKE.

plume rise represents smoldering. This smoke is dispersed from the ground with an initial vertical dispersion coefficient of 30 m. Atmospheric dispersion processes are integrated over all transport distances from within the area of prescribed-fire activity to the "impact analysis point" to estimate a concentration value for that point (fig. 12). The inverse of the smoke concentration at that point is the value used for DI.

When calculating smoke concentration resulting from plume-rise-associated smoke, the effective depth is assumed to be constant over the entire area. When a mixing height is thermally defined (i.e., in unstable or neutral conditions), this assumption is identical to that used in VSMOKE plume calculations for smoke uniformly mixed within the mixing layer. In stable conditions (no thermally defined mixing height), calculating the effect of dispersion processes over the entire area is described by Lavdas (1986). By considering dispersion over the entire area and using a single effective height, the calculation process is greatly simplified and is analogous to the process used for vertically well-mixed smoke.

Values of effective height are set by the following scheme. When mixing height is defined in unstable or neutral • daytime conditions, effective height is set to the mixing height but is restricted to a minimum value of 240 m. At night, when stable conditions often prevail-resulting in an undefined mixing height-the effective height of the uniform smoke layer is dependent on stability class. If the stability class is near neutral— night, the depth matches the mixing height (or depth of the isothermal layer), but is restricted to a range between 240 and 600 m. If the stability class is slightly stable, the uniform smoke layer depth is 180 m. If the stability class is moderately or extremely stable, the depth is 150 m.

The smoke that is very limited in plume rise in the DI model undergoes a Gaussian dispersion process (Lavdas 1986). The initial vertical dispersion coefficient for this smoke is set at 30 m, regardless of atmospheric stability conditions-unstable, stable, or neutral-day or night. The effect of stability on the smoldering smoke causes it to disperse at the rate appropriate to the assigned stability class. The functional dependence of this dispersion on downwind distance is accounted for by numerical integration of the appropriate functions for vertical dispersion coefficient over the range of distances from within the prescribed-fire activity source area to the "impact analysis point."

With all other factors equal, the uniform area source in figure 12 may be thought of as prescribed burning activity. The smoke concentration at the impact analysis point may be thought of as the averaged aggregate effect of the burning activity. As the simple inverse of that concentration, DI can be used as a measure of the burning activity possible without adverse aggregate effects from added smoke concentrations. In the absence of other sources of atmospheric pollution, the relationship between DI and acceptable burning activity might be considered directly proportional. However, the limitations of DI must be recognized. For instance, because the smoke emission source is defined as uniform and covers a wide area, DI is not an appropriate analysis tool for smoke effects from an individual plume (unless that plume happens to be 50 km-about 3 1 miles wide!). The VSMOKE plume model, not DI, should be used for single plume analysis.

The direct relationship between DI and estimated smoke concentration at the impact analysis point (fig. 12) implies that any maximum smoke concentration level set for that point would not be violated when burning activity is doubled on occasions when DI is doubled. Because DI is calculated only on a proportionate basis, the concentration criterion is never explicitly specified; therefore, DI does not directly specify an absolute acceptable level of burning activity. Designed to enable area-wide dispersion comparisons among weather regimes, DI is well suited as a basis for allocating smoke emissions from prescribed-fire activity over areas ranging from subcounty to multicounty sixes (about 25 to 10,000 square miles).

Table 4 interprets DI values. The interpretations are based on climatology, criteria for air stagnation, and prescribed weather conditions for controlled burning. Although they have been used for several years, these interpretations may be regarded as preliminary. With experience and expertise, the interpretations may be modified and the ranges redefined to best fit the fire and atmospheric patterns of a specific area.

Dispersion Index does not account for high humidity effects on visibility in smoke. Dispersion Index strictly describes areawide atmospheric capacity to disperse pollutants to or below some acceptably low criterion value for smoke concentration. In high humidity, a smoke concentration sufficiently low from an air quality assessment standpoint may generate or worsen a hazardously low visibility in smoke and fog. However, when DI is combined with relative humidity, it appears to help characterize the frequency of low visibility occurrences resulting from fog, smoke, or both.

Low Visibility Occurrence Risk Index

VSMOKE provides an estimate of risk of low visibility and smoke hazard on roadways by using the LVORI (Lavdas and Hauck 1991). Low Visibility Occurrence Risk Index is a semiquantitative, indexed variable that expresses the estimated level of risk for roadway visibility hazard with integer values from 1 to 10. A value of 1 denotes the lowest (standard) risk category and a value of 10 denotes the highest risk category. The 10 categories allow considerable flexibility and opportunity for developing multiple management strategies. Low Visibility Occurrence Risk Index values are determined directly from DI and relative humidity (RH). Low values of DI combined with very humid conditions result in the highest LVORI values, while moderate to high DI values combined with moderate to dry humidity conditions yield low LVORI values. The top part of table 5 shows LVORI values as a function of DI and RI-I. The bottom part presents interpretations of these values.

Low Visibility Occurrence Risk Index is derived from an analysis of the observed proportions of low visibility in fog, smoke, or both as reported by the Florida Highway Patrol at over 400,000 roadway accident sites during 1979-8 1. The accident reports were statistically stratified with respect to the estimated weather at the time and place of each accident. The weather estimates were based on National Weather Service surface and upper air observations at stations near or surrounding each accident site. Twice daily, upper air reports were used to estimate mixing height and transport windspeed at each surface weather station at the time of each available observation (ranging from every hour to every 3 hours). The surface station data were weighted to estimate conditions appropriate for the county where each accident occurred. Various weather parameters in the accident sites data base, including estimates of windspeed, humidity, stability class, and DI, were correlated to the proportion of reports of low visibility in smoke and/or fog found in the Florida Highway Patrol data base. Relative humidity and DI showed the strongest and most physically coherent association. The stratification of the data matched expectations based on physical mechanisms (i.e., as RH increased, DI decreased, or both, the proportion of low-visibility reports by the Florida Highway Patrol uniformly and smoothly increased). In general, statistical proportionality testing of the data showed very strong statistical significance. With the exception of categories 1 and 2, each LVORI category is statistically distinct from any other category. Tests involving DI as the sole indicator of risk were used as the basis for distinguishing between category 1 and category 2. No need for any additional categories emerged from similar tests involving only RH.

Table 5 shows the relationship between risk of visibility hazard on roadways and RH and DI. Only a small degree of smoothing was performed on the raw accident data to generate the tabular values shown, and this data smoothing was restricted to selecting values of DI and RH to group together. The smoothness of response of LVORI with increasing RH and decreasing DI lends considerable credence to the associations found in the analysis. In the bottom portion of table 5, a low LVORI value indicates a relatively low proportion of accident reports with fog, smoke, or both, a higher number indicates an increased proportion'and the likelihood of increased risk of roadway hazard resulting from low visibility in smoke. Low visibility in Florida is a relatively uncommon event. The highway patrol reported fog, smoke, or both in only 3,235 out of a total of 433,649 analyzed accident reports during the 3-year period. In these reports, 604 included smoke, 2,972 included fog, and 341 included both smoke and fog. This proportion can be as low as about 1 in 1,000 for LVORI = 1 (or 2) or about 150 times higher when LVORI = 10 (table 5).

Unfortunately, data used to develop LVORI are scarce, expensive, and time consuming to process; LVORI has not been verified by an independent data set. Until verification, this index must be regarded as a statistically well-behaved, reasonable, working hypothesis that should be used cautiously when making fire management decisions. The literal use of the level of risk given in table 5 is not recommended.

Visibility studies using observational data at National Weather Service and experimental sites have yielded dramatically different proportions of low visibility risk. For example, much higher low-visibility proportions in very humid conditions were found by Lavdas (1974) in a study of fog in coastal Georgia. Part of this difference is attributed to scatter and uncertainty associated with probable errors in the weather estimates at accident sites often geographically remote from weather stations.

Accident data sets can be **inaccurate** because law enforcement officials are not trained to make meteorological observations. The highway patrol data were screened to remove reports with obvious problems (e.g., daylight conditions reported for a **1:00** a.m. accident). Occasionally, fog would be reported with spuriously low RH estimates. These reports were accepted under the assumption that fog-like conditions were present and perhaps a result of evaporation after a local shower or generation of a plume that appeared more like fog than smoke. These reports received respect, because roadway safety is an overriding consideration in any report law enforcement officers make.

Unlike most **information** presented by VSMOKE, LVORI is given as a semi-quantitative value-an index giving a risk category, somewhat in the same fashion that an insurance risk category might be determined and described. The insurance risk analogy even applies to the source of the data: a large number of accident reports and the association of circumstances surrounding the accidents. The user should carry the insurance risk analogy one step **further:** avoid the high risk categories and lower the risk as much as practicable.

An additional degree of caution is required when using LVORI for prescribed **fire** applications within any climatic regime greatly dissimilar to that of Florida. Subjective experience in an operational forestry weather forecasting environment indicates that LVORI can be directly applied in the humid climates within a few hundred miles of the Gulf of Mexico **(Rippen,** footnote 1, page 5). However, the applicability of DI and RH relationships included in the current version of LVORI in other locations is less certain. Synoptic-scale weather patterns conducive to fog and low visibility in smoke are likely to have varying relationships to locally observed weather parameters in various climatic regions. Hazardously low visibility response in climatic areas where the frequency distributions of relative humidity, stability, windspeed, and perhaps cloud cover are markedly different from those found in Florida may be somewhat **different.** Frequencies of low visibility with respect to DI and RH could vary, or could be more closely associated with other meteorological parameters.

Significant differences in the relationships are also likely on a much smaller spatial scale. For example, fog prone areas will probably experience more hazardous conditions when the nearest RH observations indicate “marginal” conditions or risk. Areas downwind (or **"downdrift")** from water bodies or very wet areas, such as swamps or highly irrigated agricultural tracts, can experience increased and more serious visual obstruction. Subtle terrain features can induce low visibility as nearly saturated air is forced to rise and cool. Vegetative and soil differences can cause sign&ant **differences** in atmospheric radiational cooling rates and local air flow patterns that can be important in low visibility events resulting from fog, smoke, or both. In a very humid environment, a forced mixing of air masses with slightly different characteristics can trigger rapid fog formation. Background atmospheric pollutants can force widely varying visibility responses, because many pollutant constituents in smoke and other sources contain nuclei capable of forming water droplets in a process closely analogous to cloud formation. The exact nature and mixture of atmospheric pollutants at a given location will determine whether conditions must be saturated with respect to a planar surface of pure water for such smoke and fog clouds to form, which is the reason why LVORI risk levels (table 5) start to rise when RH is considerably less than 100 percent.

Installing VSMOKE

Installing

No installation steps are necessary prior to running VSMOKE. **VSMOKE.EXE** is run like any FORTRAN 77 program on the host system. However in the PC environment, an appropriate library of mathematical functions and processes must be present.

If VSMOKE.FOR (but not **VSMOKE.EXE)** has been supplied, the program must be compiled and linked like any other FORTRAN 77 source listing in the host environment. In the PC environment, the source code must be broken into segments before compilation can take place. Compiling the main program, input sections, and output sections separately has given satisfactory results.

Testing

Running the test cases will help ascertain whether the program is functioning properly on the host system. VSMOKE is a complex FORTRAN 77 algorithm that uses many routines from various software libraries. The exact nature of the executable instructions depends on the various interactions between the compiler, linker, math co-processor (if present), operating system, and computer hardware.

Test Procedures

1. Copy file **VSMOKE.I11** onto file VSMOKEJPT.

2. Run VSMOKE.

3a. If a message indicating “END OF RUN FLAG **= T"** is displayed on the screen, compare output file VSMOKE.OUT to **file VSMOKE.O11.**

3b. If the message indicates “END OF RUN FLAG = F,” or no message appears, a serious problem has occurred. First check that VSMOKEJPT properly matches **VSMOKE.I11.** If VSMOKEJPT is correct, **notify the authorized VSMOKE program maintenance agent to res**olve the **difficulty.**

4. Note any discrepancies between the output **files.**

5. Delete file VSMOKEJPT.

6. If you wish to save the output file, rename VSMOKE.OUT; otherwise delete it.

7. Repeat steps 1 through 6, using **files VSMOKE.I22, VSMOKE.I33,** and **VSMOKE.I44.**

8a. If discrepancies are nonexistent or inconsequential for the four input **files,** VSMOKE has successfully passed the testing procedure on your host system.

8b. If discrepancies are large and cannot be resolved, notes of the exact nature of the discrepancies for the errant test runs will help the authorized VSMOKE program maintenance agent **identify** and correct the problem.

The test cases are designed to test ranges of input values, exercise the various flags, and force the execution of all non-error pathway logic within VSMOKE. The values assigned to the input variables in the test cases should not be considered recommendations for any operational use.

File **VSMOKE.I11** contains the first test case:

```
60
'VSMOKE.I11 TEST CASE 1:'
36.000 76.000 5.0 1994 3 26 8 15.5 1.0 T T T 0.02
0.25
40.0 240.0 40.0 250.0 14.0 4.0 4.0 2.0 T 0.60
14 -500. -1.  30 T 1 1500. 2.0 0.0 0.0 30.0 2.5
15 -500. -1.  40 T 2 1500. 4.0 0.0 0.0 40.0 3.0
16 -500. -1.  50 T 3 1500. 6.0 0.0 0.0 40.0 3.5
17 -500. -1.  60 T 4 1500. 8.0 0.0 0.0 40.0 4.0
18 -500. -1.  70 F 4 500. 4.0 0.0 0.0 50.0 5.0
19 -500. -1.  80 F 5 240. 2.0 0.0 0.0 40.0 5.0
20 -500. -1.  90 F 6 240. 1.5 0.0 0.0 35.0 4.0
21 -500. -1. 100 F 7 240. 1.0 0.0 0.0 30.0 3.5
14 4.0E+01 1.0E+01 5.0E+01 +0.60
15 4.0E+01 1.0E+01 5.0E+01 -1.00
16 4.0E+01 1.0E+01 5.0E+02 -0.90
17 2.0E+00 4.0E+01 1.0E+00 -0.75
18 1.0E+00 1.0E+00 1.0E-02 +0.50
19 1.0E-01 1.0E+00 1.0E-03 0.00
20 1.0E-02 1.0E-01 0.0E+00 +1.00
21 1.0E-04 1.0x-02 1.0E-05 +0.80
```

File **VSMOKE.I22** contains the second test case:

```
63
'VSMOKE.I22 - VSMOKE''S SECOND TEST CASE SOMEWHERE HALF NEAR TO DOWN UNDER:'
-35.067 -145.383 -9.25 2002 04 13 6 11.0 1.0 T F F 0.0 0.0
640.0 1920.0 15.0 50.0 11.0 0.75 1.00 0.25 F -0.75
2002041311 -46. 845.6 20 T 2 240. 0.5 0.0 30.0 0.0 0.0
2002041312 +123. 992.3 25 T 2 7000. 10.0 0.0 30.0 0.0 0.0
2002041313 +32. 1013.25 30 T 3 1500. 8.0 0.0 30.0 0.0 0.0
2002041314 50. 1065.3 16 T 3 1500. 4.0 0.0 30.0 0.0 0.0
2002041315 44. 888.0 9 T 4 500. 4.0 0.0 30.0 0.0 0.0
2002041316 60. 700.0 37 T 4 5000. 4.0 0.0 30.0 0.0 0.0
```

File **VSMOKE.I33** contains the third test case:

```
60
'VSMOKE.I33 - TEST CASE 3:'
30.000 90.000 6.0 1993 1 4 1 14.00 0.0 F T T 0.05 0.125
0.0 0.0 0.0 0.0 13.50 0.0 0.0 0.0 T 2.0
1993010414 59. 1014.0 55 7. 9 13000. 850. 3.5 0.0 0.0 125. 8.0
1993010414 30.0 2.0 15.0 -0.95
```

File VSMOKE.I44 contains the fourth case:

```
66
'VSMOKE.I44 TEST CASE 4:'
35.583 76.217 4.0 1996 5 4 21 12.75 1.0 F F T 0.25 0.25
10.0 50.0 17.0 315.6 13.0 4.0 6.0 4.0 T +0.60
1245 75. 1012.4 33 3.  0 99999. 1200.  3.6   0.0   0.0  30.0  2.5
1345 79. 1012.4 29 5.  1 99999. 1500.  5.8   5.0  10.0  35.0  5.0
1445 82. 1013.0 27 6.  4 99999. 1750.  4.7  30.0  40.0 100.0 20.0
1545 90. 1011.9 18 5. 10 25000. 2645.  6.3 100.0 100.0 30.0  4.0
1645 69. 1013.8 75 37. 10  600. 1000. 23.5  10.0  10.0  20.0  3.0
1745 78. 1012.7 48 16. 10 15000. 1500. 8.0   0.0   0.0  40.0  3.0
1845 81. 1010.5 39 6. 10  5000. 1700.  5.9   5.0   5.0  50.0  8.0
1945 74. 1009.8 44 3. 10 15000.  700.  2.8  20.0  20.0   0.0  0.0
2045 73. 1010.4 48 5. 10  7000.  500.  5.0  50.0   0.0   0.0  0.0
2145 70. 1010.4 52 0. 10  4000.  300.  1.5  90.0   0.0   0.0  0.5
2245 68. 1011.9 56 0.  7  4000.  240.  1.0  65.0   5.0   5.0  1.0
2345 63. 1012.3 64 0.  8  4000.  240.  1.0   0.0   0.0  40.0  3.5
0045 61. 1012.0 69 3.  5 99999.  240.  1.5   0.0   0.0   0.0  0.0
0145 59. 1012.2 70 4.  4 99999.  240.  2.2   0.0   0.0   0.0  0.0
0245 57. 1012.5 78 9.  2 99999.  240.  4.6   1.0   1.0  10.0  2.0
0345 54 1011.8 85 10.  0 99999.  240.  5.1   5.0   3.0  20.0  3.0
0445 53. 1011.5 89 7.  0 99999.  240.  5.7   5.0   3.0  20.0  3.5
0545 52. 1011.7 93 6.  4 99999.  240.  6.1   0.0   0..0  40.0  4.0
0645 53. 1011.6 100 0. 10     0.  400.  2.0   0.0   0.0  40.0  4.0
0745 57. 1010.2 94 0.  6   500.  600.  5.5   0.0   0.0  30.0  3.0
0845 68. 1009.0 76 0.  1 99999.  900.  7.1   0.0   0.0  30.0  3.0
```

VSMOKE Program Characteristics

Program Files

A brief description of the files used in VSMOKE follows:

1. **VSMOKE.DOC—a** documentation file for program VSMOKE, which should be consulted before VSMORE is run.

2. **VSMOKE.FOR—contains** the VSMOKE FORTRAN 77 source code listing for use in the **PC** or similar environment. To compile the program, this source listing is copied, then broken into three sections: the first contains the main program, the second contains IN'DATA and all subprograms referenced directly or indirectly by **INDATA,** and the third contains output-related subprograms (subroutines CHIOUT and VOUTPR and all subprograms referenced directly or **indirectly** by subroutine CHIOUT).

2a. **VSMOKEMN.FOR—contains** the FORTRAN 77 source listing for the main program of **VSMOKE.**

2b. **VSMOKEIP.FOR—contains** the FORTRAN 77 source listing for the **input-**related subprograms of VSMOKE.

2c. VSMOKEOT.FOR—contains the FORTRAN 77 source listing for the output-related subprograms of VSMOKE.

3. **VSMOKEMN.OBJ—contains** the object code generated by compiling the main program of **VSMOKE.**

4. **VSMOKEIP.OBJ—contains** the object code generated by compiling the input related subprograms of VSMOKE.

5. **VSMOKEOT.OBJ—contains** the object code generated by compiling the output related subprograms of VSMOKE environment.

6. **VSMOKE.EXE—co**ntains the executable code generated by linking the three VSMOKE object code **files, VSMOKEMN.OBJ,** VSMOKEIP.OBJ, and **VSMOKEOT.OBJ.**

7. **VSMOKE.IPT—is** the single input file for **VSMOKE;** it must be present when **VSMOKE** is run; formatting and required data are described in VSMOKE Input **Requirements.**

8. **VSMOKE.OUT—is** the output **file** generated when VSMOKE is run; any data already present in this file at run time are lost.

9. **VSMOKE.I**—(where** ** is a multiple of 11, up to 44) are sample input **files** included for testing purposes.

10. **VSMOKE.O**—(where** ** is a multiple of 11, up to 44) are output files, corresponding to each sample input **file,** included for testing purposes.

11. **VSMOKE.SCR—a** pseudo-scratch output file generated during a VSMOKE run; if the final output file, VSMOKE.OUT, cannot be successfully completed, this file may be kept at the end of the run; otherwise, it is deleted during the run after **VSMOKE.OUT** is generated.

VSMOKE uses FORTRAN 77 "list-directed" input from file VSMOKEJPT in all cases. List-directed output is used only to echo-print the contents of the input file and diagnose some errors. The remaining output is formatted.

All input required to run VSMOKE is provided through file **VSMOKE.IPT.** "List-directed" read statements input data to this file. The VSMOKEJPT data must be given in the exact order and format described in Input Requirements.

Nearly all output generated by **VSMOKE** is written onto file **VSMOKE.OUT.** Formatted output statements assume that FORTRAN 77 formatted output printing conventions are followed by the host system. When generated by formatted WRITE statements, the VSMOKE.OUT output file consists of up to 127 printed characters per line. Up to 60 lines per individual page are generated within the period-by-period and worst-case analysis sections of the output. The output file begins with an echo-print section. The length and characteristics of this section depend on the length of the VSMOKEJPT input file and how host computer and software systems handle FORTRAN 77 list-directed output.

Source Code-Characteristics and Structure

The FORTRAN source code for VSMOKE is contained in file **VSMOKE.FOR.** The source code fully meets ANSI Standard X3.9.1978 (FORTRAN 77 programming language-full language), ANSI (1978). The code is thoroughly commented, both with respect to programming logic and underlying mathematical and scientific bases.

VSMOKE consists of 34 subprogram units, including 1 main, 13 subroutines, 19 functions, and 1 block data **unit.** The main program, VSMOKE, opens the input and output files, **VSMOKE.IPT** and VSMOKE.SCR, and calls the controlling input and output subprograms, **INDATA** and CHIOUT. All input is handled in **INDATA,** subprogram LSMKWX, or subprogram EMSPRI. Subprogram **INDATA** calls LSMKWX when stability class is not available in the input file; **INDATA** calls EMSPRI when period-by-period emissions related data are included in the input file. With the exception of echo-printing of input data, any necessary error diagnostics, and an end-of-run message, all VSMOKE-controlled output is initially handled in CHIOUT or WOCOUT. Subprogram CHIOUT calls WOCOUT to process worst conditions found among all analyzed periods. Called by the main program, subprogram VOUTPR generates final output.

Double precision mathematical processing is invoked selectively within subprograms YRATIO and EDEPTH and completely in subprogram QNORML. Double precision is required within these subprograms unless at least roughly 60 bits are available for actual single precision real number processing on the host system Single precision processing is used exclusively for floating point processing in all other subprograms.

Visual Overview

Figure 13 provides a **12-page** overview of program **VSMOKE** and names subprograms, identifies input/output points, and shows major loops and decision points of the program.

Subprogram Descriptions

A brief description of each subprogram follows:

VSMOKE-main program initializes program name and version number for the page header output lines, opens files **VSMOKE.IPT** and VSMOKELSCR, calls subroutines **INDATA,** CHIOUT, and VOUTPR, and stops the run. During a normal run, the only output generated by the main program is an end-of-run message to the screen. In case of errors, other messages may be generated.

INDATA-subroutine reads and error checks fire and weather data, then directly or indirectly determines weather and emissions variables for each **period;** if needed, calls subroutine LSMKWX to determine stability class; calls either subroutine **EMSPRI** or EMSPRC, depending on whether period-by-period emission rate related values are to be read in or calculated. This subroutine also generates **echo-**print output to **VSMOKE.SCR;** in case of error, calls subroutine VOUTPR.

LSMKWX-subroutine reads and error checks weather data when that data does not include stability class: determines stability class **from** the data and solar ephemeris variables; calls subroutines ASTRO and SUNANG, and references function **ITURNR;** generates echo-print output to VSMOKELSCR. In case of error, calls subroutine VOUTPR.

EMSPRI-subroutine reads and error checks period-by-period emission rate related data; generates echo-print output to VSMOKELSCR, in case of error, calls subroutine VOUTPR.

EMSPRC-subroutine calculates period-by-period emission rate related **data.**[12]

IDAYYR-function determines day of year from year, month, and day.

ASTRO-subroutine computes solar ephemeris variables for a given day.

SUNANG-subroutine computes solar elevation angle.

ITURNR—function determines stability class from surface weather and solar elevation angle.

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[12] Subprogram EMSPRC was codeveloped by Leonidas G. Lavdas, Research Meteorologist, USDA Forest Service, Juliette, GA, and Clay D. Gillespie, formerly a systems analyst with the Georgia Forestry Commission, Dry Branch, GA.

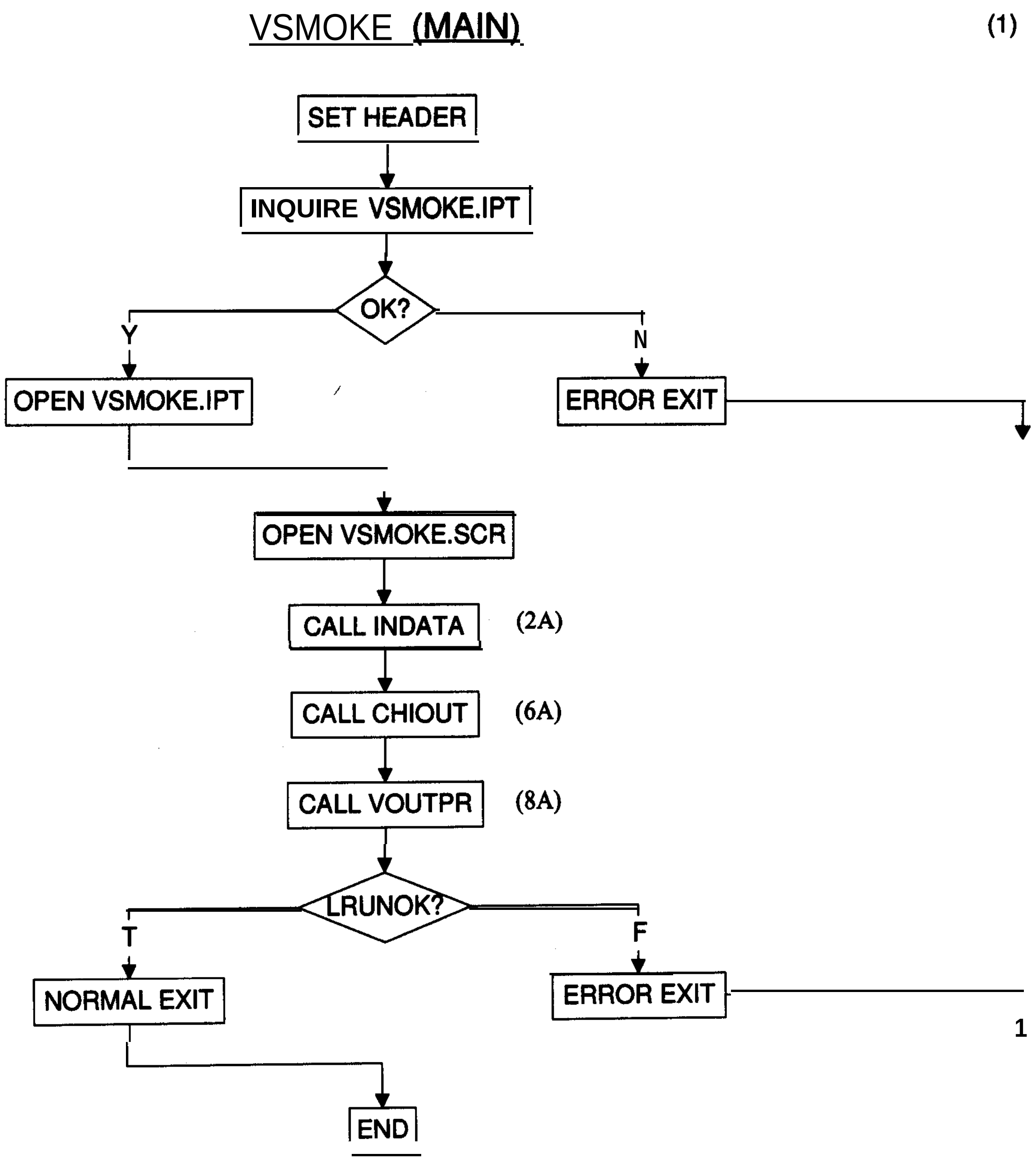

Figure U-Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version **19950128—Continued** on pages 60-70.

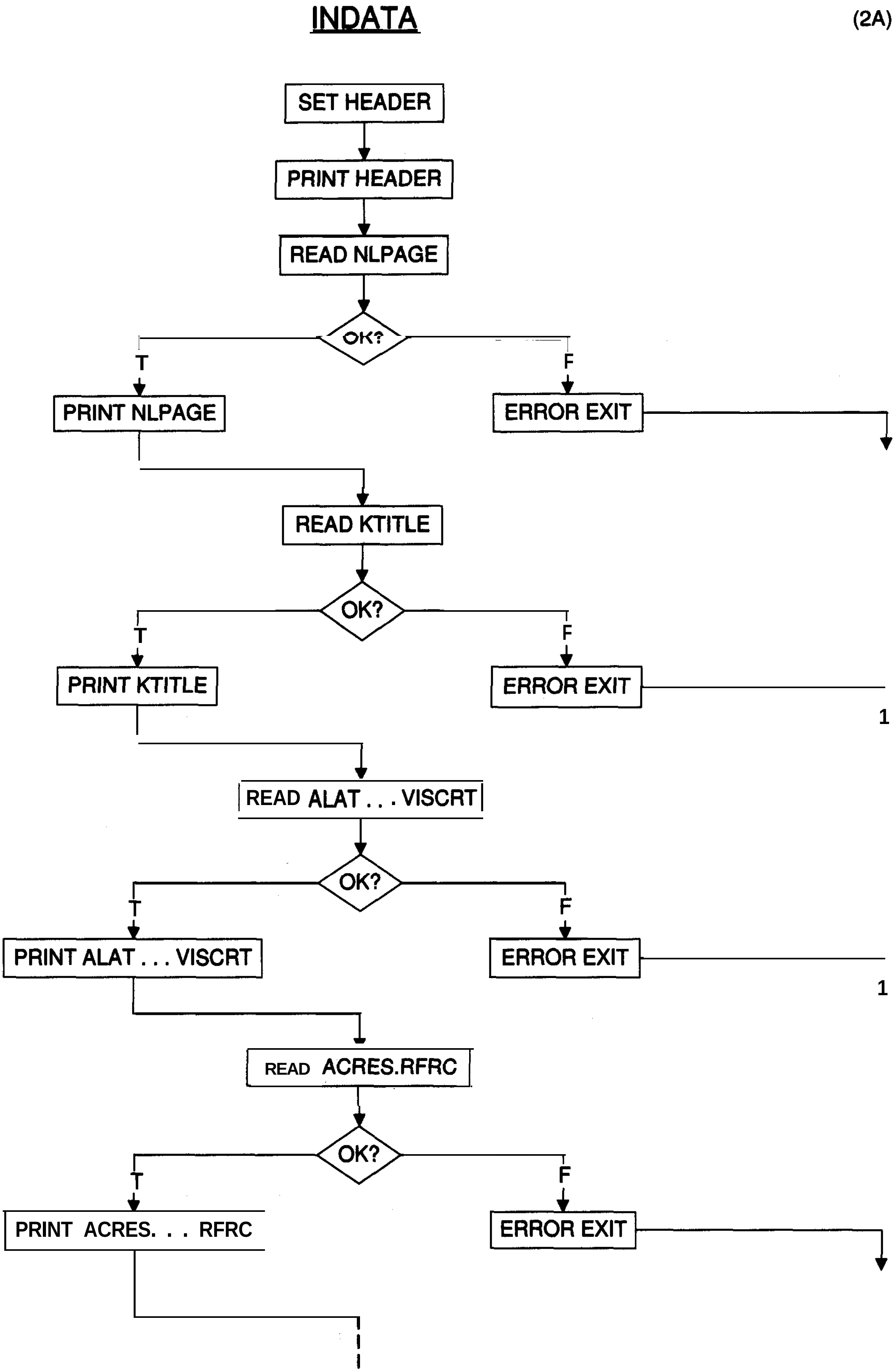

Figure 13-Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version 19950128—Continued.

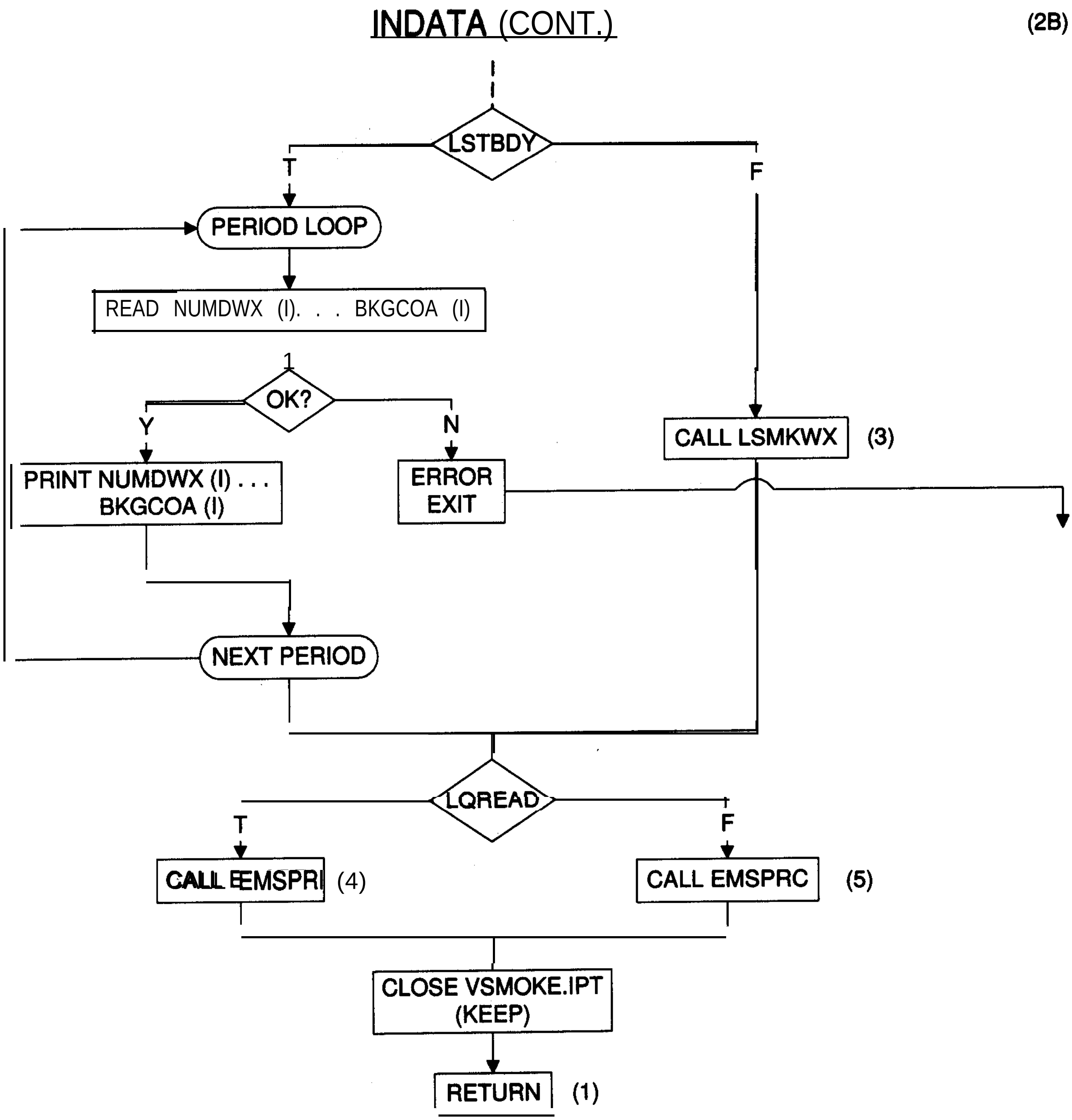

Figure 13-Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version19950128—Continued.

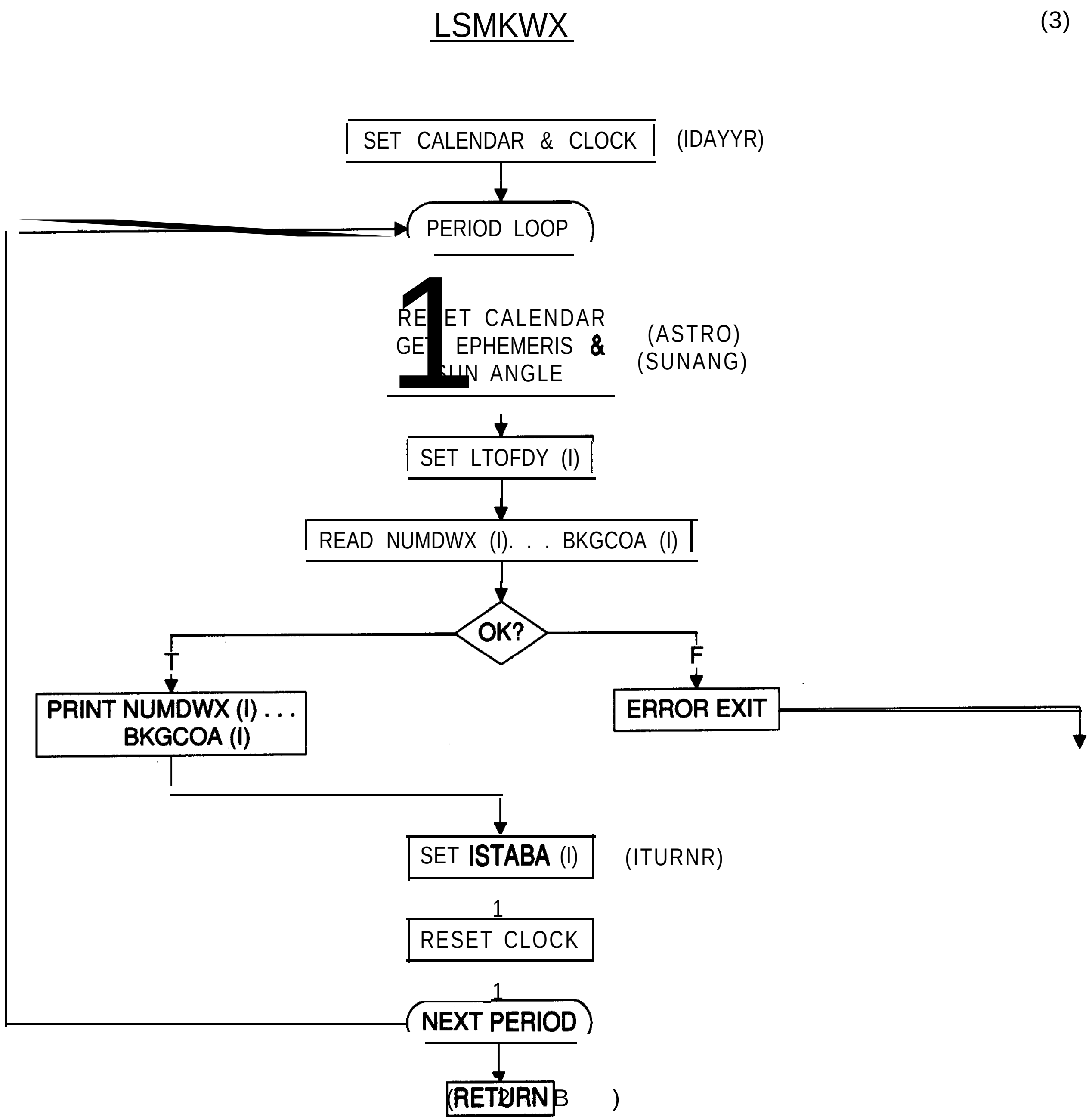

Figure 13-Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version **19950128—Continued.**

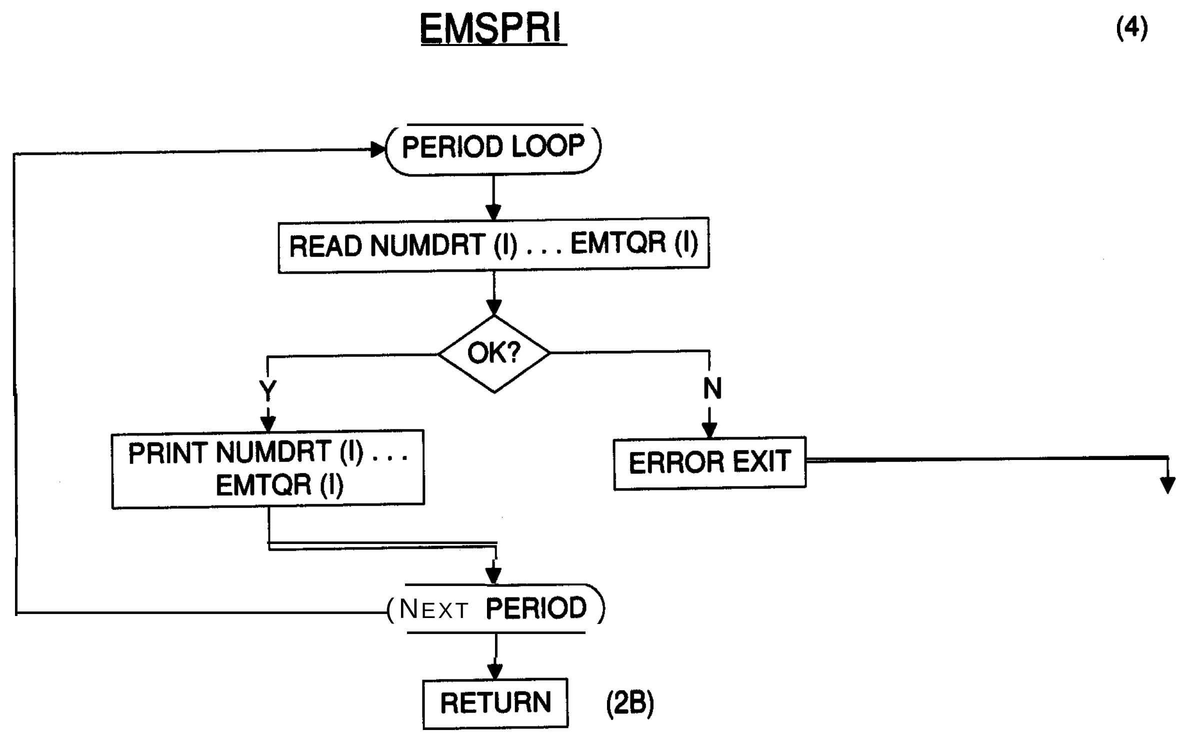

Figure 13—Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version 19950128—Continued.

EMSPRC (5)

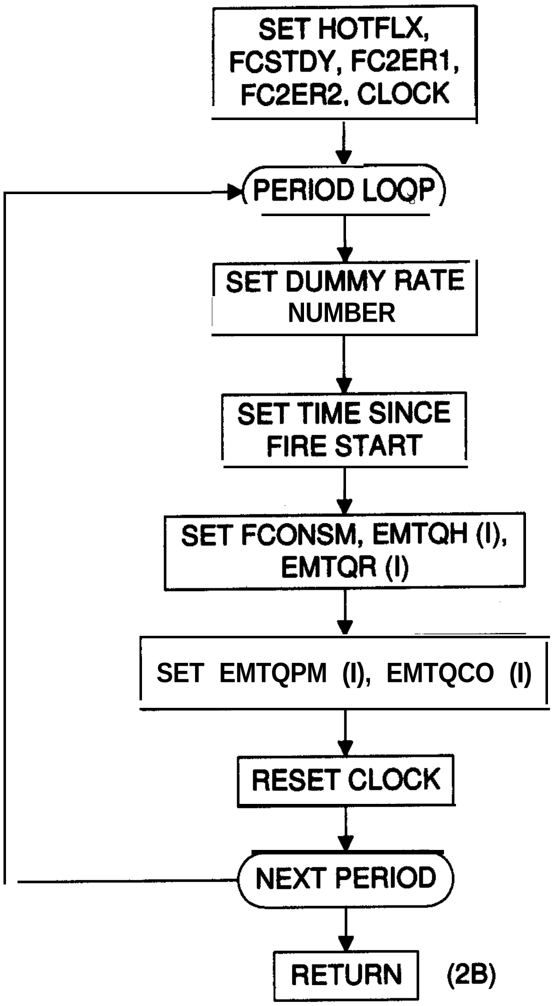

Figure 13-Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version 19950128—Continued.

CHIOUT

(6A)

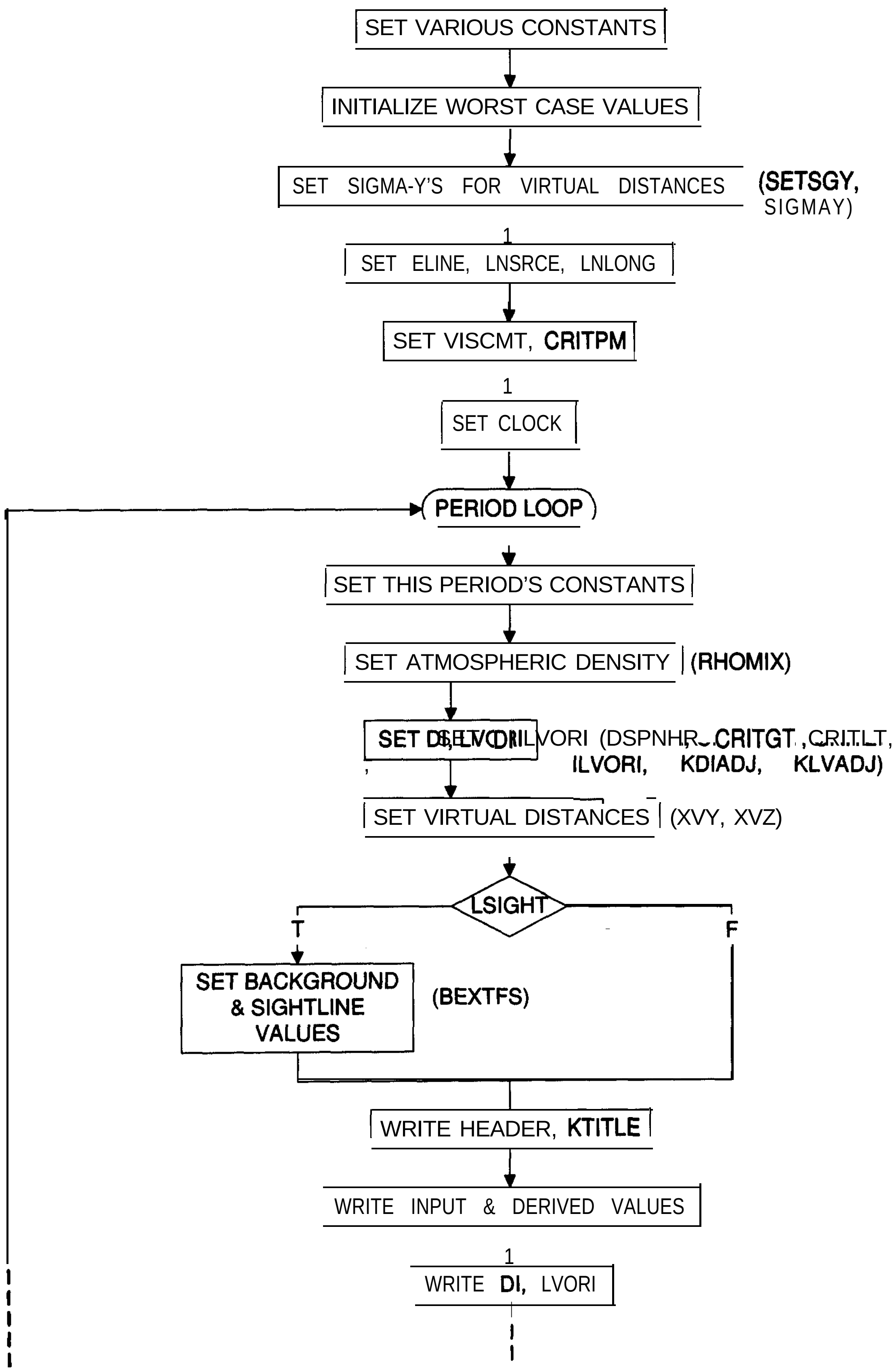

Figure 13-Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version 19950128—Continued.

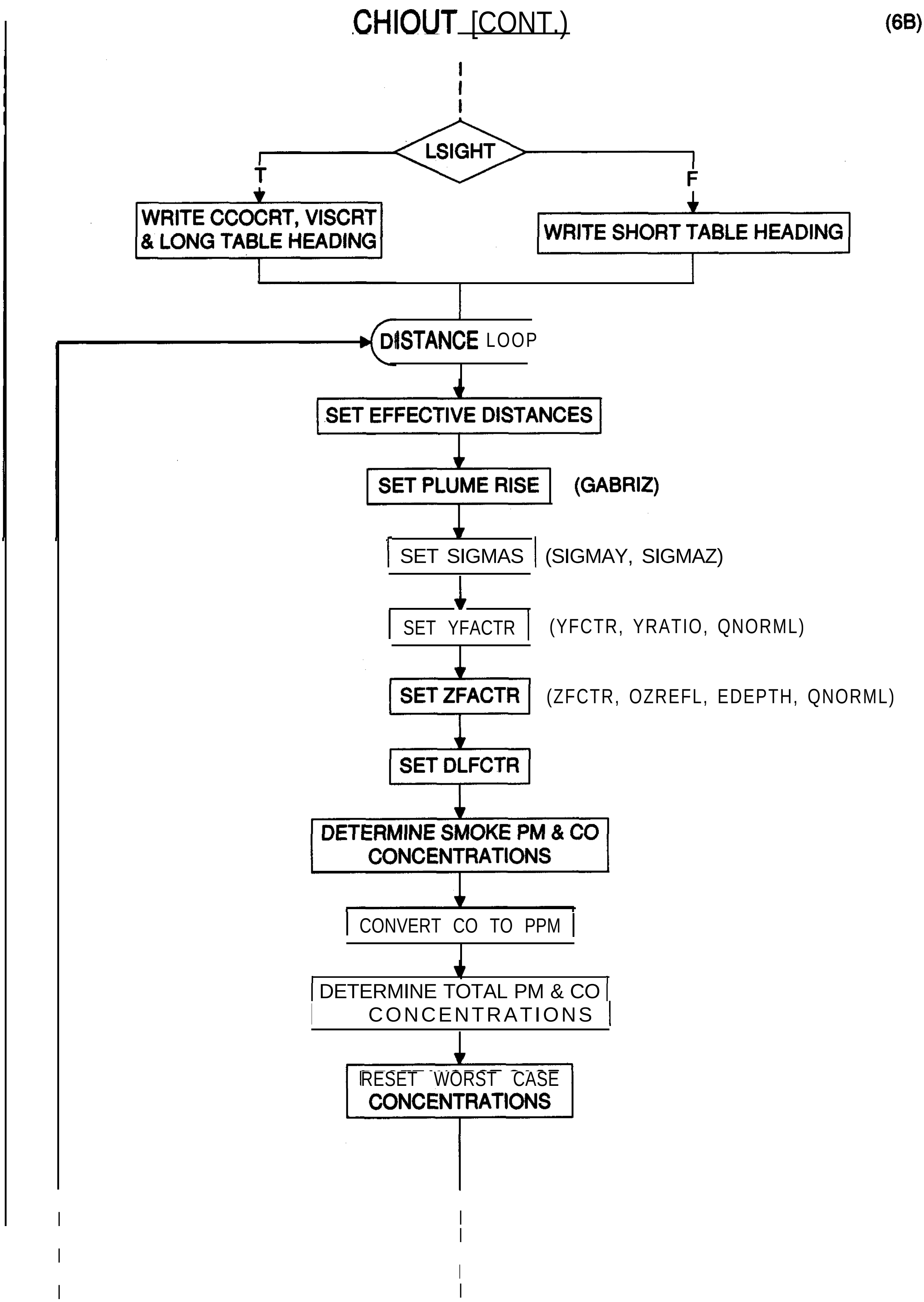

Figure 13—Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version 19950128—Continued.

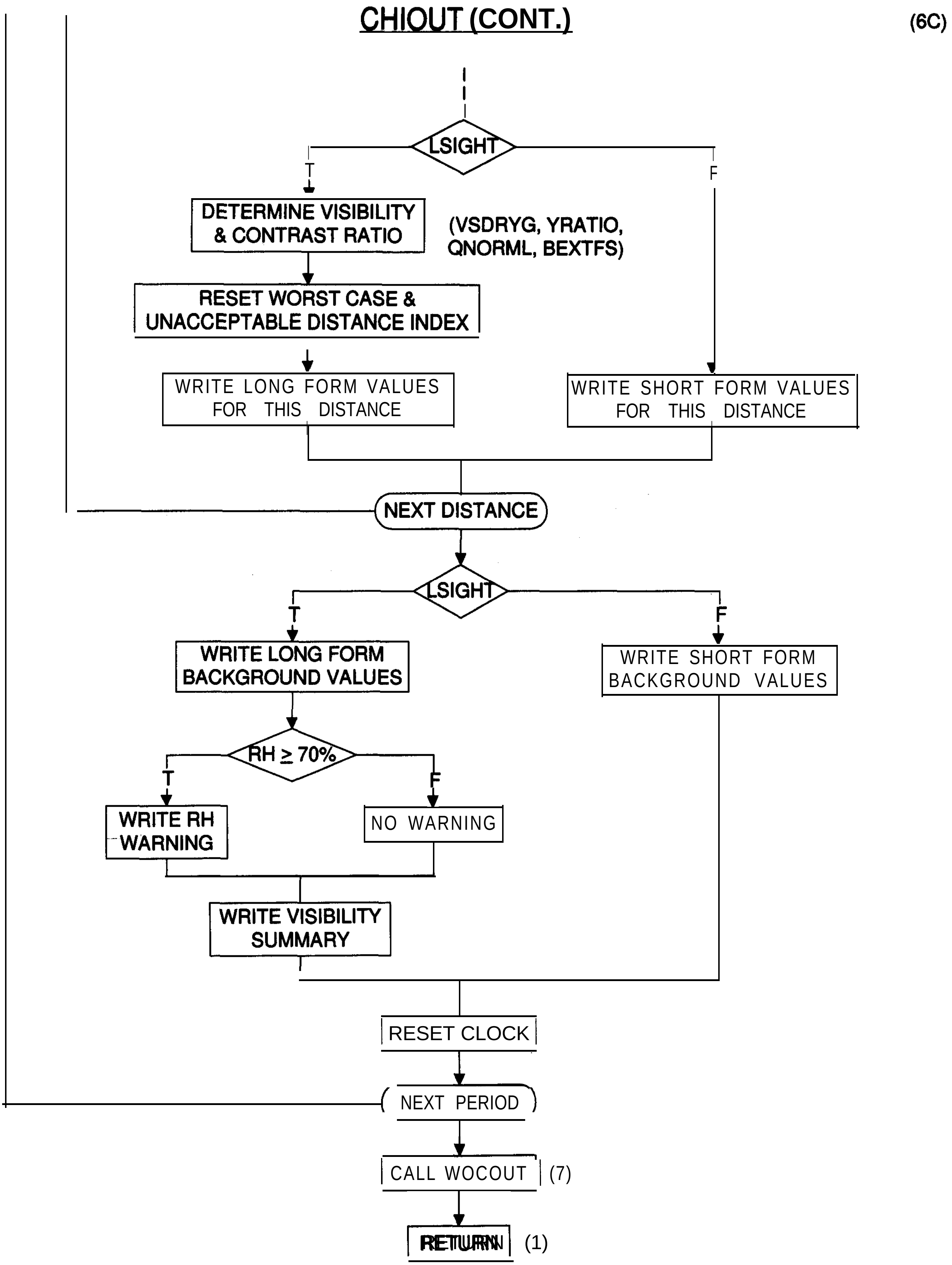

Figure 13—Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version 19950128—Continued.

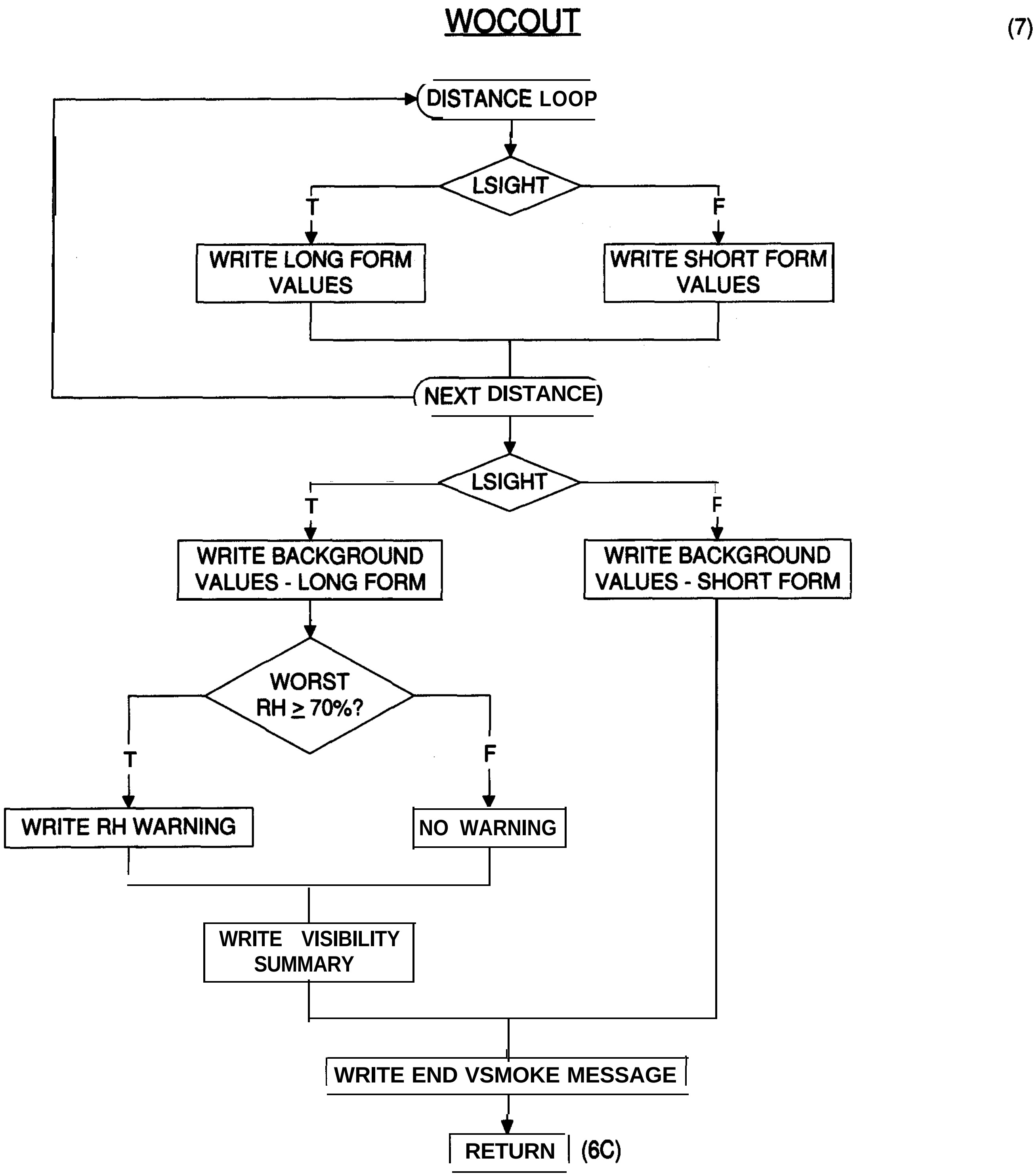

Figure 13-Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version **19950128—Continued.**

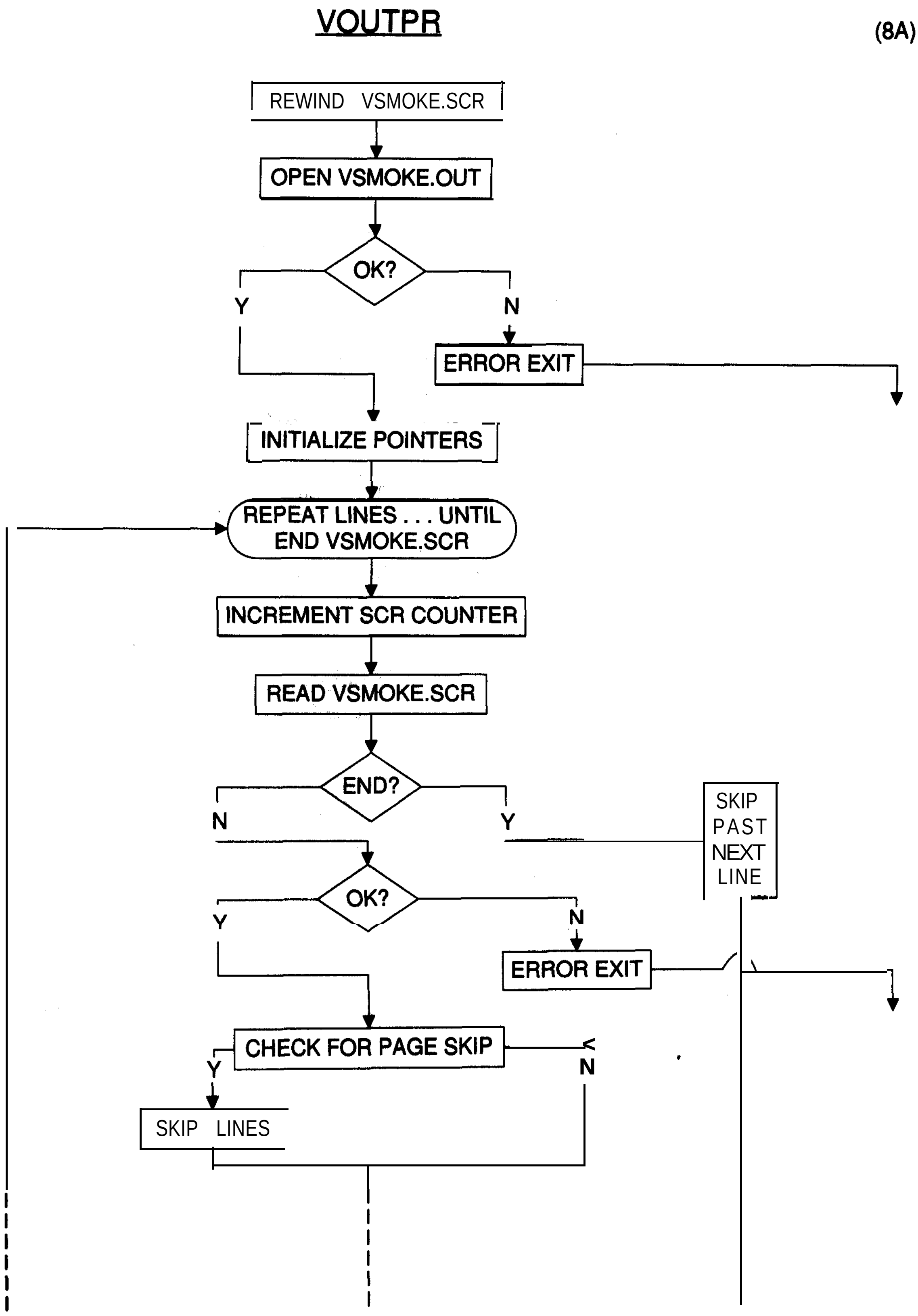

Figure 13-Flowchart of FORTRAN 77 Computer Code for VSMOKE, Version **19950128—Continued.**

VOUTPR (CONT.)

(8B)

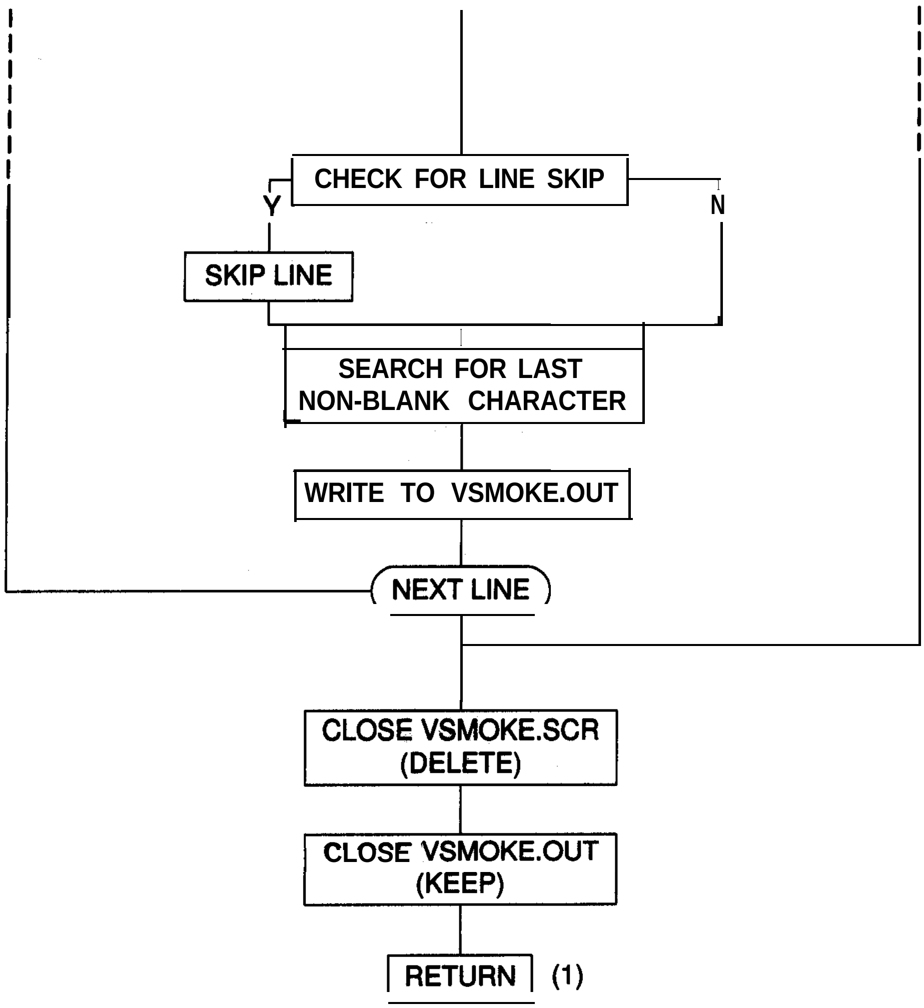

Figure 13-Flowchart of FORTRAN 77 Computer Code for **VSMOKE,** Version **19950128—Continued.**

CHIOUT—subroutine controls calculations and output of selected input and intermediate variables, DI, LVORI, downwind centerline particulate matter and carbon monoxide concentrations, and dry weather crossplume visibilities and contrast ratios, on a period-by-period basis; calls subroutines SETSGY, **YFCTR,** DSPNPR, and VSDRYG, and references functions **RHOMIX,** KDIADJ, ILVORI, ICLVADJ, XVY, XVZ, BEXTPS, GABRIZ, SIGMAY, SIGMAZ, and ZPCTR to determine period-by-period data; all period-by-period output is generated directly to file VSMOKE.SCR, and calls WOCOUT to generate worst-case output from all periods analyzed.

RHOMIX-function computes density of a moist atmosphere; vapor pressure is determined following equation (8) of Buck (198 1).

DSPNPR—(Lavdas 1986) subroutine computes DI; references functions CRITGT and CRITLT.

CRITGT—(Lavdas 1986) function aids in calculating DI.

CRITLT—(Lavdas 1986) function aids in calculating DI.

KDIADJ—character function determines DI adjective corresponding to its input DI value.

ILVORI-function calculates LVORI.

KLVADJ—character function determines LVORI adjective corresponding to the input LVORI value.

GABRIZ—function computes plume rise at a given downwind distance resulting **from** the sensible heat emissions from a fire **(Briggs** 1975); slightly modified as noted in comments within the code.

SETSGY—subroutine presets values of horizontal dispersion coefficient for a wide range of downwind distances for later use in "virtual distance" calculations, and references function SIGMAY.

XVY-function computes horizontal "virtual distance" associated with a given horizontal dispersion coefficient.

SIGMAY-function computes horizontal dispersion coefficient.

YFCTR—subroutine computes the effects of all horizontal dispersion processes for a point or line source and references function YRATIO for a "significantly long" line source only.

YRATIO-function computes ratio of concentrations from a finite line source to those from an infinite line source, and references function QNORML to obtain area under portions of the normal distribution curve.

XVZ-function computes vertical "virtual distance" associated with a given vertical dispersion coefficient.

SIGMAZ-function computes vertical dispersion coefficient.

ZFCTR-function computes the **effects** of all vertical dispersion processes for the variety of possible initial vertical plume **configurations** possible in VSMOKE, and references functions **OZREFL** and EDEPTH.

OZREFL-function computes the effects of vertical exponential terms in the Gaussian plume equation's "reflections" terms **(from** the ground and top of the mixing layer) for a source and receptor at any height between the ground and top of the mixing layer.

EDEPTH-function computes the "effective depth" of a source with emissions initially uniformly dispersed to some depth in the vertical and then subsequently acted upon by Gaussian dispersion processes (the "effective depth" is relative to the concentrations at a ground-level receptor only), and references function QNORML to obtain area under portions of the normal distribution curve.

VSDRYG—subroutine computes dry weather horizontal crossplume visibility and contrast ratio for a given downwind distance resulting **from** a single smoke plume and constant background, references function BEXTFS to obtain extinction coefficient, and references function YRATIO.

BEXTFS-function computes extinction coefficient using the relationship according to Tangren (1982) as modified by Tangren in 1985 (fig. 14, footnote a, page 84).

QNORML—double precision function that determines the area of the standard normal distribution that lies between a point x and "approaching infinity," where the sign of x and "approaching **infinity"** are the same.

BDSDWN—block data subprogram that sets all downwind distances used in VSMOKE; these range **from** 1 m to 1000 km.

WOCOUT—subroutine processes and handles output for worst relative humidity, DI, LVORI, particulate matter and carbon monoxide concentrations, and dry weather crossplume visibilities and contrast ratios; references functions KDIADJ and **KLVADJ;** and generates output to VSMOKE.SCR.

VOUTPR—subroutine; opens and generates the final output file, VSMOKE.OUT, from data in the pseudo-scratch output file, VSMOKE.SCR, generates screen output only if it encounters an error.

Source Code Revision

Further research or future applications of VSMOKE may eventually dictate that alternatives to the Briggs (1975) relationships be used to estimate plume rise. The current version of VSMOKE is restricted to the Briggs formulas. However, VSMOKE is designed to make revisions to its plume rise calculation procedures a straightforward process. Plume rise calculations are performed in one function, GABRIZ. The sole reference to GABRIZ is in subroutine CHIOUT. User-designed subprogram alternatives to GABRIZ can be added to the existing code. A control structure to select the appropriate plume rise subprogram should also be added within subroutine CHIOUT at the point where GABRIZ is referenced. The selection among alternative plume rise subprograms can be dynamically controlled by adding a new user input variable. In addition, if any of the user's plume rise routines depend on data not included in the VSMOKE input variables, provision for including and processing the additional data would also be necessary.

Any effort to revise the methods used in VSMOKE to either distribute the smoke that rises or determine its impact on downwind ground-level concentrations is not a simple process.' Any significant changes to the program methodology would require extensive revision to and thorough testing of a number of subprograms in the VSMOKE FORTRAN 77 code.

To use alternatives to the Pasquill-Gifford-Turner system to determine dispersion coefficients in VSMOKE would require a program revision. VSMOKE is designed to make revisions to its dispersion coefficient calculation techniques (including incorporation of a selection methodology) a straightforward process. Alternative subprograms to the current dispersion coefficient calculation functions, SIGMAY and SIGMAZ, should be provided. Alternative subprograms for their inverse functions, XVY and XVZ, which calculate "virtual distances" are also required. References to all four functions should be revised by including a selection structure to control the subprogram references. One reference to each of the four functions is made in subroutine CHIOUT. One additional reference to SIGMAY is made in subroutine SETSGY, which presets σ_Y values used to obtain horizontal virtual distances. Revising the method of obtaining σ_Y would probably also involve an alternative to subroutine SETSGY—one reference to SETSGY is made in subroutine CHIOUT. Dynamic control of the dispersion coefficient selection process can be achieved by adding appropriate user input variables. In addition, provision must be made for adding any input variables (such as wind variability coefficients) required by an alternative scheme.

Any user knowledgeable in programming scientific models in the FORTRAN 77 language should be able to make these revisions. However, careful attention should be given to the effects of plume rise, dispersion coefficient, or any other revisions to VSMOKE on the model's "bottom line," i.e., its ground-level concentration and sightline related estimates, before using any revision(s) in an operational environment.

VSMOKE Input Requirements

Because all VSMOKE data are input through FORTRAN 77 list-directed READ statements, users must be particularly familiar with the requirements associated with FORTRAN 77 list-directed input on their system. While this input technique allows considerable flexibility, system dependent rules not defined by

ANSI (1978) can affect the performance of VSMOKE. Moreover, care must be exercised to ensure that all variables appear in their proper order and according to their specified format, which in **list-directed** processing is controlled by the input variable type (i.e., REAL vs. **INTEGER** vs. LOGICAL vs. CHARACTER).

The input file **VSMOKE.IPT** must be available to the executable program at the **beginning** of a VSMOKE run. The user is free to generate the data within **VSMOKE.IPT** by any convenient means before VSMOKE is run. Intermediate "working" **files** will be necessary if automated pre-processing programs are to be used to generate a subset of the required data. That subset would then be merged with the remaining required data before VSMOKE run time to meet all input requirements. Although the integrity of the data within **VSMOKE.IPT** is maintained during a VSMOKE run, input files should be archived under unique names and copied to VSMOKEIPT when a VSMOKE run is to be made. VSMOKEIPT becomes a de facto working file when these operating procedures are followed.

Input Overview

The input file contains variables that give processing instructions, describe the fire, specify its atmospheric environment, and set criteria for acceptable smoke and roadway visibility management. A significant proportion of the data are input on a period-by-period basis. To some extent, the layout of the data depends on the values of two LOGICAL variables: LSTBDY and **LQREAD.**

Because all user input to VSMOKE is through FORTRAN 77 list-directed read statements, the following rules of this input process are most likely to affect the VSMOKE user:

1. Variables within the input file must agree in type (REAL, **INTEGER,** LOGICAL, or CHARACTER) with the variable input list in the READ statement.

2. Generally in VSMOKE, variables should be separated by a comma or one to a few blank spaces.

3. An end-of-record mark (e.g., a new line in an input file would usually be detect& as an end-of-record mark) is generally treated as a variable separator, unless it is part of a CHARACTER variable (enclosed within bracketing apostrophes).

4. A decimal point is optional within a REAL variable that has a whole integer value.

5. Powers of 10 exponential notation (e.g., **1.35E+05** or **0.135E+06,** for 135000.0; and **1.35E-04** or **0.135E-03,** for 0.000135) may be used to specify a REAL variable. Judicious use of this notation form may result in more accurate representation of the REAL value within VSMOKE under certain conditions.

6. A decimal point is illegal within an INTEGER variable.

7. A plus sign (+) is optional within either a REAL or INTEGER variable.

8. A minus sign (-) must be used as necessary within a REAL or INTEGER variable or within the exponent of a REAL variable.

9. A LOGICAL variable is specified as T or F; TRUE or FALSE or **.TRUE.** or **.FALSE.** are also acceptable.

10. A CHARACTER variable is delineated by apostrophes ('), which are not counted as part of the **CHARACTER** variable; if an apostrophe is a part of the CHARACTER variable, use two adjacent apostrophes (''); only one becomes part of the CHARACTER variable.

11. The length of a CHARACTER variable in the input file should not exceed the specified length of the corresponding CHARACTER variable in the input list of the READ statement (in VSMOKE, the only CHARACTER input variable is **KTITLE** which can be up to 72 characters long).

12. The input file CHARACTER value may be shorter than the specified length of the corresponding CHARACTER variable in the input list; blanks are used to "fill" the unused positions of the CHARACTER variable (e.g., using '12' in **VSMOKE.IPT** for **KTITLE** causes positions 3 to 72 of **KTITLE** to be blanks).

Programming language FORTRAN Standard X3.9.1978 (ANSI **1978),** as implemented on the host computer system, should be consulted if questions or problems arise associated with specifying a variable for the VSMOKE input process.

Input Variables

The following input variables must be included in file **VSMOKE.IPT.** These variables are considered on a line-by-line basis, with each line corresponding to the execution of a READ statement in VSMOKE. Input lines with multiple non-character data items may be broken into two or more shorter lines where the break between the lines serves **as a** variable separator within the input file.

Input line #I-Read the number of lines per page to be used in the output file; in subprogram **INDATA,** the READ statement appears as follows:

READ(INPT,*,ERR=900,END=950,IOSTAT=IERRNO) NLPAGE

where

NLPAGE = INTEGER, number of lines per page of output to be generated within final output file, **VSMOKE.OUT;** must be within the range 60 to 66.

Input line #2-Read title of run; in subprogram **INDATA,** the READ statement appears as follows:

READ(INPT,*,ERR=910,END=960,IOSTAT=IERRNO) KTITLE

where

KTITLE = **CHARACTER*72,** Title of run, up to 72 characters; apostrophes(') must appear immediately before and after the title in order to conform to FORTRAN 77 **list-directed** input rules for CHARACTER data.

Input line #3-Read place and time of fire, input weather data format, flags for emissions data, and sightline criteria; unless otherwise noted, values are input as REAL variables; in subprogram **INDATA,** the READ statement appears as follows:

READ(INPT,*,ERR=920,END=970,IOSTAT=IERRNO) ALAT, ALONG,TIMZON,IYEAR,MO,IDAY,NPRIOD,HRSTRT, HRNTVL,LSTBDY,LQREAD,LSIGHT,CC0CRT,VISCRT

where

ALAT = Latitude in decimal degrees **north;** valid range is -90.0 to **+90.0.**

ALONG = Longitude in decimal degrees west; valid range is -240.0 to **+240.0.**

TIMZGN = Time zone in decimal hours behind UTC (i.e., Greenwich), EDT = ***4.0,*** EST = 5.0, CDT = 5.0, CST = 6.0, etc., with fractions allowed for locations such as Newfoundland; valid range is -18.0 to **+18.0.**

IYEAR = INTEGER, year (leading **19-** or **20-** optional).

MO = **INTEGER,** month of year (January = 1, December = 12).

IDAY = INTEGER, day of month.

NPRIOD = INTEGER, number of periods in simulation; valid range is 1 to 100.

HRSTRT = Start time of simulation in decimal hours, relative to **IYEAR,** MO, and **IDAY;** any value is acceptable, but the usual range is 0.0000 to 23.9999.

HRNTVL = Length of time interval between adjacent individual periods during simulation in decimal hours; unless NPRIOD = 1, HRNTVL must be at least 0.0001 hours; if NPRIOD = 1, supply a dummy **value.**[13]

LSTBDY = LOGICAL, TRUE if stability class and daylight data are to be input; FALSE if program must calculate these variables.

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[13] A dummy value means any value legal for the type of variable in the input/output list. The value is read into the program, but is otherwise not used.

LQREAD = LOGICAL, TRUE if period-by-period total emission rates, total sensible heat emission rate, and proportion of emissions subject to plume rise for each NPRIOD are to be input; FALSE if program must calculate these variables.

LSIGHT = LOGICAL, TRUE if crossplume sightline variable estimates (visibility and contrast ratio) are needed; FALSE if not needed-omitting sightline calculations can save significant computational time.

CCOCRT = Critical contrast ratio upon which **crossplume** visibility estimates are based; 0.02 is used for airport visual range; a somewhat higher value might be appropriate for the general population of licensed drivers; a much higher value is required for appreciating scenic vistas; not used if LSIGHT is FALSE, but a dummy value must still be provided; if LSIGHT is TRUE, the valid range of CCOCRT is 0.000001 to 0.999999.

VISCRT = Visibility criterion for roadway safety or other intended purpose in miles; for roadway safety, set it to at least 0.0947 miles (500 feet); other reasonable values for roadway safety include **0.125, 0.25, 0.5,** and 1 **.0** miles; not used if LSIGHT is FALSE, but a dummy value must still be provided; if LSIGHT is TRUE, VISCRT must be at least l.OE-07, and no greater than 9999.99 miles.

Input fine **#4—Read** tire and smoke characteristics data; unless otherwise noted, values are input as REAL variables; in subprogram **INDATA,** the READ statement appears as follows:

READ(INPT,*,ERR=930,END=980,IOSTAT=IERRNO)
ACRES,TONS,EFPM,EFCO,TFIRE,THOT,TCONST,TDECAY,LGRISE,RFRC

where

ACRES = Area of fire as a smoke source in acres; zero or negative specifies point source modeling.

TONS = Total mass of **fuel** consumed in short tons; not used if LQREAD is TRUE, but a dummy value must still be provided; if LQREAD is FALSE, TONS must be non-negative.

EFPM = Emission factor in pounds per ton for particulate matter; in the current version of VSMOKE, "particulate matter" may mean total or any size class, but the input value of EFPM must be consistent with the input value(s) of **BKGPMA(I);** see U.S. EPA **(1985-90)** for appropriate values; not used if LQREAD is TRUE, but a dummy value must still be provided; if LQREAD is FALSE, EFPM must be non-negative.

EFCO = Emission factor in pounds per ton for carbon monoxide; see U.S. EPA (1985-90) for appropriate values; not used if LQREAD is TRUE, but a dummy value must still be provided; if LQREAD is FALSE, EFCO must be non-negative.

TFIRE = Start time of fire in decimal hours; relative to IYEAR, MO, and IDAY (usual range, 0.0000 to 23.9999).

THOT = Duration of convective period of fire in decimal hours, beginning at time TFIRE; not used if LQREAD is TRUE, but a dummy value must still be provided; if LQREAD is FALSE, THOT must be non-negative, and THOT must not exceed TCONST.

TCONST = Duration of constant emissions period in decimal hours, beginning at time TFIRE; not used if LQREAD is TRUE, but a dummy value must still be provided; if LQREAD is FALSE, TCONST must be non-negative, TCONST must be at least as great as THOT, and TCONST + TDECAY must exceed zero.

TDECAY = Exponential decay constant for smoke emissions in decimal hours; the decay constant is applied beginning at time, (TFIRE + TCONST), as in: EXP (-(TSIM - (TFIRE + TCONST)) / TDECAY), where TSIM is the current simulation time in VSMOKE; not used if LQREAD is TRUE, but a dummy value must still be provided; if LQREAD is FALSE, TDECAY must be non-negative, and TCONST +TDECAY must exceed zero.

LGRISE = LOGICAL, TRUE if plume is assumed to rise gradually to its final height as it travels downwind; FALSE if plume is assumed to immediately attain its final rise.

RFRC = Proportion of emissions subject to plume rise; +1.0, denotes all emissions rise to the height predicted by plume rise equations for a stack (Briggs 1975) and undergo model dispersion processes initially from that height only; zero denotes no plume rise and dispersion is initially from ground level only; a positive fraction denotes the plume is initially split between full plume height and ground level; a negative fraction denotes that the rising proportion of smoke (as expressed by the absolute value of RFRC) is initially uniformly distributed in the vertical from ground level to the Briggs (1975) height and then this uniform vertical distribution is subjected to model dispersion processes as it moves downwind, the remaining smoke is dispersed from ground level (if -1.0, all smoke is initially uniformly distributed in the vertical, if -0.5, half is initially uniform and the other half starts from ground level); not used if LQREAD is TRUE, but a dummy value must still be provided; if LQREAD is FALSE, the valid range of RFRC is -1.0 to +1.0; a value of +0.6 is used by SFFLP (1976) and described by Lavdas (1978); an unpublished analysis of the Lavdas data shows that a value of -0.75 yields an improved fit.

IF LSTBDY = TRUE; THEN, INPUT LINES #5 to (NPRIOD + 4):

Loop through periods, using I as the index variable, reading period-by-period weather data; the input data list includes daylight and stability class; the data are assumed synchronous with the values of HRSTRT and HRNTVL and must be synchronous with the optional period-by-period emissions data; unless otherwise noted, values are input as REAL variables; within the appropriate **IF** block and DO loop in subprogram **INDATA,** the READ statement appears as follows:

READ(INPT,*,ERR=940,END=990,IOSTAT=IERRNO) NUMDWX(I),TTA(I), PPA(I),IRHA(I),LTOFDY(I),ISTABA(I), AMIXA(I),UA(I),OYINTA(I), OZINTA(I),BKGPMA(I),BKGCOA(I)

where

NUMDWX(I) = INTEGER, this period's dummy weather data number to aid in file bookkeeping.

TTA(I) = This period's temperature at the surface in degrees Fahrenheit (a value approaching or below absolute zero, i.e., less than -459.0 F, is interpreted as defaulting to the U.S. Standard Atmosphere value for sea level, 59.0 **F).**

PPA(I) = This period's atmospheric pressure at the surface in millibars (mb) (a value approaching or less than zero, i.e., less than 0.1 mb, is interpreted as defaulting to the U.S. Standard Atmosphere value for sea level, 10 13.25 mb).

IRHA(I) = INTEGER, this period's relative humidity in percent; valid range is 0 to 100.

LTOFDY(I) = LOGICAL, set to TRUE if this period is after sunrise and before sunset; otherwise, set to FALSE.

ISTABA(I) = **INTEGER,** this period's stability class (Turner 1964); valid range is 1 to 7,

where

1 = extremely unstable
2 = moderately unstable
3 = slightly unstable
4 = near neutral
5 = slightly stable
6 = moderately stable
7 = extremely stable

AMIXA(I) = This period's mixing height in meters; valid range is 1 **.0** to 10000.0 m.

UA(I) = This period's transport windspeed in meters per second (m/s); must be at least 0.1 **m/s.**

OYINTA(I) = This period's "initial" horizontal crosswind dispersion at the source in meters; must be non-negative.

OZINTA(I) = This period's "initial" vertical dispersion at the source in meters (not including **RFRC/EMTQR(I)** plume rise related effects); must be non-negative.

BKGPMA(I) = This period's background concentration of particulate matter in micrograms per cubic meter **($\mu g\ m^{-3}$);** in the current version of VSMOKE, "particulate matter" may mean total or any size class, but the input value(s) of **BKGPMA(I)** must be consistent with the input value of EFPM (if LQREAD = FALSE) or with the input value(s) of **EMTQPM(I)** (if LQREAD = TRUE); must be non-negative.

BKGCOA(I) = This period's background concentration of carbon monoxide in parts per million (ppm); must be non-negative.

ELSE **IF** LSTBDY = FALSE; THEN, INPUT LINES **#5** to (NPRIOD + 4):

Loop through periods, using I as the index variable, reading period-by-period weather data; the input data list does not include daylight or stability class; the data are assumed synchronous with the values of HRSTRT and HRNTVL and must be synchronous with the optional period-by-period emissions data; unless otherwise noted, values are input as REAL variables; within the appropriate DO loop in subprogram LSMKWX, the READ statement appears as follows:

READ(INPT,*,ERR=900,END=950,IOSTAT=IERRNO) NUMDWX(I),TTA(I), PPA(I),IRHA(I),WSSFC,ICOVER,CEIL, AMIXA(I),UA(I),OYINTA(I), OZINTA(I),BKGPMA(I),BKGCOA(I)

where

NUMDWX(I) = INTEGER, this period's dummy weather data number to aid in file bookkeeping.

TTA(I) = This period's temperature at the surface in degrees Fahrenheit (a value approaching or below absolute zero, i.e., less than -459.0 F, is interpreted as defaulting to the U.S. Standard Atmosphere value for sea level, 59.0 **F).**

PPA(I) = This period's atmospheric pressure at the surface in millibars (a value approaching or less than zero, i.e., less than 0.1 mb, is interpreted as defaulting to the U.S. Standard Atmosphere value for sea level, 1013.25 mb).

IRHA(I) = INTEGER, this period's relative humidity in percent; valid range is 0 to 100.

(Note: The next three values are used to help determine this period's stability class, stored in array ISTABA.)

WSSFC = This period's surface windspeed in knots; must be non-negative.

ICOVER = INTEGER, this period's opaque cloud cover in tenths; valid range is 0 to 10.

CEIL = This period's cloud ceiling height in feet; if ceiling is unlimited, use 99999. feet; if sky is obscured, use vertical visibility; must be non-negative.

AMIXA(I) = This period's mixing height in meters; valid range is 1 .O to 10000.0 m.

UA(I) = This period's transport windspeed in meters per second; must be at least 0.1 **m/s.**

OYINTA(I) = This period's "initial" horizontal crosswind dispersion at the source in meters; must be non-negative.

OZINTA(I) = This period's "initial" vertical dispersion at the source in meters (not including **RFRC/EMTQR(I)** plume rise related effects); must be non-negative.

BKGPMA(I) = This period's background concentration of particulate matter in micrograms per cubic meter; in the current version of VSMOKE, "particulate matter" may mean total or any size class, but the input value(s) of **BKGPMA(I)** must be consistent with the input value of EFPM (if LQREAD **=** FALSE) or with the input value(s) of **EMTQPM(I)** (if LQREAD = TRUE); must be non-negative.

BKGCOA(I) = This period's background concentration of carbon monoxide in parts per million; must be non-negative.

END LSTBDY BLOCK IF. **..THEN. ..ELSE.**

IF LQREAD = TRUE; THEN INPUT LINES # **(NPERIOD** + 5) to (2 * NPRIOD + **4):**

Loop through periods, using I as the index variable, reading period-by-period emission rate related data; data are assumed synchronous with the values of HRSTRT and HRNTVL and must be synchronous with the period-by-period weather data; unless otherwise noted, values are input as REAL variables; within the appropriate DO loop in subprogram EMSPRI, the READ statement appears as follows:

```
READ(INPT,*,ERR=900,END=950,IOSTAT=IERRNO)
NUMDRT(I),EMTQPM(I),EMTQCO(I),EMTQH(I),EMTQR(I)
```

where

NUMDRT(I) = INTEGER, this period's dummy emission rate related data number to aid in file bookkeeping.

EMTQPM(I) = This period's total source emission rate of particulate matter in grams per second; in the current version of VSMOKE, "particulate matter" may mean total or any size class, but the input value(s) of **EMTQPM(I)** must be consistent with the input value(s) of **BKGPMA(I)**; see U.S. EPA (1985-90) for further information; must be non-negative.

EMTQCO(I) = This period's total source emission rate of carbon monoxide in grams per second; see U.S. EPA (1985-90) for further information; must be non-negative.

EMTQH(I) = This period's total sensible heat emission rate in megawatts; can be determined by total rate of fuel consumption times sensible heat released per unit mass of fuel consumed, must be non-negative.

EMTQR(I) = Proportion of emissions subject to plume rise; if +1 .O, denotes all emissions rise to the height predicted by plume rise equations for a stack (Briggs 1975), and undergo model dispersion processes initially from that height only; if zero, denotes no plume rise and dispersion is initially from ground level only; a positive fraction denotes the plume is initially split between full plume height and ground level; a negative fraction denotes that the rising proportion of smoke (as expressed by the absolute value of **EMTQR(I)**) is initially uniformly distributed in the vertical from ground level to the Briggs (1975) height, and then this uniform vertical distribution is subjected to model dispersion processes as it moves downwind, the remaining smoke is dispersed from ground level (e.g., if -1.0, all smoke is initially uniformly distributed in the vertical, if -0.5, half is initially uniform and the other half starts from ground level); the valid range is -1 .O to +1 .0; a value of +0.6 is used by SFFLP (1976) and described by Lavdas (1978); an unpublished analysis of the Lavdas data shows that a value of -0.75 yields an improved fit.

END LQREAD BLOCK IF.

VSMOKE Output

Output Overview

VSMOKE output is primarily generated to one file, VSMOKE.OUT. An end-of-run message and any error diagnostics are also output to the screen. When VSMOKE is run, any pre-existing data within VSMOKE.OUT are lost. If the contents of VSMOKE.OUT are of continuing importance, archiving the output data before another VSMOKE run is performed is necessary (e.g., by copying the contents of VSMOKE.OUT to another file).

In the PC environment, a "scratch" output file, VSMOKE.SCR, holds VSMOKE results until the model run is virtually complete. At the end of the run, VSMOKE.SCR results are processed into the final output file, VSMOKE.OUT. This allows the program to use "column 1 FORTRAN printer processing" commands to control output layout. Because "column 1" commands are not followed in the PC environment, an intermediate scratch file is used. As a scratch file, **VSMOKE.SCR** should be treated as a “reserved file name.” Any pm-existing file with that name will ordinarily be lost during a VSMOKE run.

The **final** output file layout is intended to facilitate the design of post-processor programs while maintaining an easy-to-read 132-column printout. Distinct delimiters, readily detected either by eye or by automated post-processor, designate either a specific section of the output or a notice of an error condition. When a correctly formatted printout is generated, the delimiters double as page headers. The line and **column** placement of output values is as consistent as is practicable, depending on the values of only two LOGICAL input variables. A flag near the end of the output file indicates the proper execution of the VSMOKE run. The flag should reduce the chance of error in job streams that include VSMOKE output as a component of further automated processing.

The following discussion describes how the output data in file VSMOKE.OUT is organized (see fig. 14 for an outline). Output consists of three sections: (1) an echo-print of the input data read in by the model, (2) a period-by-period analysis, and (3) a worst-case summary analysis constructed from the period-by-period output. The length of the output is dependent on the input data. The length of the echo-print section (one or more pages) depends on the amount of input data read by the program and the characteristics of the host computer system and software packages. The layout of the echo-print section is also processor dependent, but the layout of the period-by-period and worst-case summary sections is controlled by the VSMOKE program. Usually, the majority of **VSMOKE.OUT** data consists of the period-by-period analysis. **Each** analyzed period generates one page of output, consisting of up to 6,800 characters. The worst-case summary generates the **final** page, consisting of up to 4,200 characters.

The most important factor in the length of the overall output file is the number of periods analyzed. Although this value is specified by the user, the number of periods actually analyzed depends on the number of periods with significant emissions (i.e., a period with few or no smoke emissions generates no direct output). When running the maximum number of periods permitted **(100),** VSMOKE has generated an output file of nearly 750,000 bytes.

In a few unusual situations, the output format may vary from the outline (fig. 14). When **VSMOKE** detects an error, a new finalpage is generated, giving a diagnosis of the error condition. Should the input values for TFIRE, HRSTRT, HRNTVL, and NPRIOD result in no model simulation time occurring while the fire is emitting a significant amount of pollutant constituents, no period-by-period analysis is generated. Should any individual period lack significant emissions of any pollutant, no output is generated for that period. Finally, in the PC environment, should problems occur in opening or writing the **final** output file, **VSMOKE.OUT,** the pseudo-scratch output file, VSMOKE.SCR, is saved for user inspection.

I. Initial section:

An "echo-print" section of the data successfully read from the **VSMOKE.IPT** input file. This section is at least one page in length and may be longer, depending on the amount of data read into the VSMOKE run. For example, if the input value for number of periods is high, the echo-print section will be lengthy.

II. Period-by-period section, one page for each analyzed period:

A. Emissions, weather, and other data used to determine the concentration and (optional) sightline estimates for the given period.

B. Dispersion Index and associated adjective.

C. Low Visibility Occurrence Risk Index and associated interpretation.

D. A table giving smoke impact variables with respect to 3 1 logarithmically-spaced downwind distances; each line consists of data specifying the downwind distance, with other variables including:

1. Information about the rise or depth of the smoke plume.
2. Information about the horizontal and vertical crosswind extent of the smoke.
3. Pollutant constituent concentration estimates (particulate matter and carbon monoxide) resulting from the single fire plus background level.
4. Optional single fire, dry weather crossplume visibility estimates, based on the input background particulate matter concentration, the input contrast ratio criterion, the estimated plume characteristics at particular downwind distances, and assumptions based on the work of Tangren (1982; 1985[a]).
5. Optional single fire dry weather contrast ratio estimates, determined in a manner similar to crossplume visibilities and applicable for a sightline length equal to the input visibility criterion.

III. Worst-case summary section, one final page:

A presentation of the worst-case RH, DI, LVORI, pollutant constituent concentrations, and optional dry weather crossplume visibilities and contrast ratios found in the period-by-period analysis. This is followed by a "run OK" flag and an end-of-run message.

[a]Personal communication. 1985. C.D. Tangren, mathematical statistician, USDA Forest Service, Southeastern Forest Experiment Station, 320 Green Street, Athens, GA 30602.

Figure 14—Outline of VSMOKE output file, VSMOKE.OUT

Interpretation

Section *1:* Echo-print-This section starts with Line 1 as a header which consists of a series of colons (:), followed by program name and version number (e.g., PROGRAM VSMOKE • VERSION 19950 128) where the version number is in yyyymmdd format, followed by a series of colons. The format of the rest of Section 1 is dependent on the host system, because it is primarily generated by FORTRAN 77 list-directed output statements.

Section 2: Analysis for each period with significant emissions-The first line of each page in Section 2 contains a header similar to Section 1; however, a series of plus signs (+) replace the colons. In general, NPRIOD period/pages appear in Section 2. If the fire does not generate at least 1 microgram per second of either particulate matter or carbon monoxide emissions in a given period, that period is omitted. Therefore, Section 2 output may be entirely omitted for a VSMOKE run (e.g., if **TFIRE** and/or HRSTRT are erroneously input, resulting in all periods occurring before the start of the fire). Barring such unusual circumstances, the line-by-line output of each period appears as described in Appendix III.

Section 3: Worst-case analysis for all periods with significant emissions--The worst-case analysis is constructed entirely from the period-by-period analysis of Section 2. Each variable is individually considered. For example, the worst particulate matter concentration 1 .OOO km downwind is not necessarily from the same period as the worst carbon monoxide concentration 10.000 km downwind. The first line of the final page contains a header similar to the headers used in other sections, but a series of equals signs (=) replaces the colons or plus signs. Following the worst-case analysis, the fmal message in this section gives the value of the program's "run OK" flag and an end-of-run message. The value of the "run OK" flag is also output to the screen. When no errors are encountered, this message is the only VSMOKE-controlled output to the screen. Barring unusual circumstances, the line-by-line output of the worst-case analysis appears as described in Appendix **III.**

Error Handling

In the case of errors with files or input data, the program will give diagnostic messages and kill the run. A **final** page of output, in effect an Error Section with a distinctive header line to signal an error condition, is generated as described in Appendix III. A brief error message is also output to the screen. The screen message will also inform the user if the pseudo-scratch output file, VSMOKE.SCR, has been saved for inspection. If possible, the **final** output file, VSMOKE.OUT, will be generated during the error handling process, obviating the need to keep the pseudo-scratch file.

Error conditions detected and handled by the host system may also be encountered. In these cases, the output to the files and screen will be host system dependent. In case of processor-controlled errors, the pseudo-scratch output file, VSMOKE.SCR, will probably be available for inspection, while the **final** output file, VSMOKE.OUT, may not have been opened when the error condition **occurred.**

Application Summary

The results of a VSMOKE run are primarily intended to give an overview of the probable air quality impact from a single forestry-prescribed fire. The effects of a user-specified uniform background level of pollutants are included in the VSMOKE estimates. Because the physics of ground fires in general are sufficiently similar to that of forestry-prescribed fires, VSMOKE can be used to estimate air quality impact from sources such as wildfires, agricultural burns, and other ground-based open combustion sources.

VSMOKE smoke concentration estimates are applicable at ground level along the downwind centerline of the smoke trajectory. No attempt is made in VSMOKE to geometrically specify the trajectory of the smoke. The direction of smoke transport must be determined independently. Allowance must be made for both the horizontal width of the smoke plume and the variability and uncertainty associated with wind direction. The width of the smoke plume depends on both the area of the smoke source and the horizontal dispersion of smoke.

Table 2 presents the horizontal "spread angles" of the plume for which the concentrations of a point source fall to 0.1 times the centerline value. The spread angles are a function of stability class and downwind distance. VSMOKE output displays the stability class **(ISTAB)** used during each analysis period in the tabular information in the top **one-fifth** of each analysis period/page. The VSMOKE downwind distance dependent tabular output in the lower two-thirds of each analysis period/page also includes estimates of the horizontal dispersion coefficient, σ_Y, with respect to downwind distance for each analysis period. For a point source, smoke concentrations **from** a fire will fall to 0.1 times the centerline value at approximately 2.15 times the value of σ_Y to either side of the centerline. The relationship for a finite line source is more complex but may be approximated as a horizontal displacement of 0.5 times E_{LINE} plus 2.15 times σ_Y to achieve a fall to 0.1 times the centerline value, where E_{LINE} is the effective line length of the pollution source. E_{LINE} is displayed in the tabular information in the top **one-fifth** of each analysis period/page.

To account for wind variations and fluctuations, the user must allow for the probability that concentrations and visibilities similar to VSMOKE centerline estimates will occur at considerable angles to the nominal smoke trajectory. At a minimum, an assumption that the centerline concentrations could occur **30°** to either side of an observed steady downwind direction is required, as has been recommended by SFFLP (1976) and Wade and Lunsford (1989). A recent study of wind direction persistence and forecast accuracy (Lavdas 1993) indicates that at Macon, GA, the probability of the wind maintaining a direction within **30°** on an hour-to-hour basis is only 71 percent. Of course, wind direction is even less consistent with forecasts. Because the National Weather Service forecasts are given to only eight compass points (i.e., northeast, east, southeast, south, southwest, west, northwest, and north), a forecast can never be more precise than within plus or minus 22.5". Moreover, the Lavdas (1993) study found that early morning forecasts were "correct" only 37 percent of the time and were "off by only one category" an additional 40 percent of the time.

Frequently at night, wind direction may be inconsistent, or a forecast may specify "near **calm"** or "light and variable" wind. Smoke can still be carried significant distances by light wind currents under such regimes. For instance, an NWS anemometer will not turn until the wind reaches about 3 knots - fast enough to transport smoke over 50 km (more than 30 miles) during a night. In these cases, concentric circles about the fire site are the only reasonable basis for setting geometrically based criteria for smoke management decisions. Use of concentric circles is also required for stronger windspeeds with highly variable directions and for any management situation where wind direction behavior is uncertain.

VSMOKE smoke concentration estimates are given for particulate matter and carbon monoxide at 3 1 logarithmically spaced downwind distances, ranging from 0.1 to 100 km (table 6). The concentration estimates apply at ground level along the centerline of the smoke trajectory and include the user input background concentration values. Particulate matter in VSMOKE is "generic," i.e., it may include all total suspended particulate matter or only a portion of the total (e.g., PM10 - particulate matter of 10 micrometers **(μm)** diameter or less, or PM2.5 - **particulate** matter of 2.5 pm diameter or less), as reflected by the user's input **values** for input background concentration array, BKGPMA, and the emission factor for the **fire,** EFPM, or the emission rate array, EMTQPM. Thus, the user determines whether the VSMOKE particulate matter concentration analysis applies to total suspended particulate matter, **PM10,** PM2.5, or some other fraction of particulate matter.

VSMOKE particulate matter concentration estimates are given in micrograms per cubic meter, the same units currently used to defme the National Ambient Air Quality Standards (NAAQS) for **PM10.** The short-term NAAQS standards are the most applicable to prescribed **fire** analyses using VSMOKE. The shortest term NAAQS standard for PM10 is 150 **$\mu g\ m^{-3}$,** averaged over a 24-hour period, not to be exceeded more than once a year. Even if VSMOKE estimates of PM10 concentrations are in excess of the NAAQS **24-hour** average standard, that standard may still be met by the analyzed fire. The geometric locations experiencing centerline smoke concentrations will often change during the course of a burn. Moreover, many, if not most, prescribed fires will not affect air quality for a full **24-hour** period.

However, NAAQS values are not specifically designed to safeguard roadway safety. A smoke impact **remaining** within the PM10 NAAQS limits may cause a relatively short-lived, but severe, impact on roadway visibility, even if the relative humidity is less than 70 percent. For example, a **fire** causes a 6,000 **$\mu g\ m^{-3}$** PM10 concentration for 30 minutes, but then the smoke goes elsewhere, the fire goes completely out, or both, leaving a background of 20 **$\mu g\ m^{-3}$** for the rest of the day. The 24-hour average concentration would be less than 150 **$\mu g\ m^{-3}$,** but the peak concentration could be high enough to cause a significant visibility hazard. In humid conditions, hazardously low visibilities are highly probable with much lower PM 10 smoke concentrations.

VSMOKE carbon monoxide (CO) concentration estimates are given in parts per million with respect to mass per unit volume of CO and the total atmosphere+the same units currently used to define the NAAQS standards for CO. The shortest term NAAQS standards for carbon monoxide are 9.0 ppm for an **8-hour** average and 35 ppm for a l-hour average. Near sea level, these values nominally correspond to 10,000 and 40,000 $\mu g\ m^{-3}$. These standards are designed to keep the proportion of CO within the blood of exposed persons below 2 percent.

Assuming that realistic background and emission factors for both particulate matter and carbon monoxide are input, concentration estimates for PM10 will more readily exceed the NAAQS standards than CO estimates in most situations. Fires involving organic soils may be an exception. **When** most combustion in an organic soil fire is glowing or smoldering, the emission factor for CO may greatly exceed that for any of the regulated size classes of particulate matter. An organic soil **fire** can pose a threat as great or greater to the NAAQS CO standards than to the PM10 standard.

The downwind dependent **crossplume** visibility and contrast ratio estimates, which optionally accompany the tabular smoke concentration estimates, are applicable only if the relative humidity is less than 70 percent. At higher humidities, the likelihood of smoke particle size growth resulting from condensation of water vapor **increases—thus** the scattering and extinction capabilities of individual smoke particles can greatly increase. As relative humidity values approach saturation (i.e., approach 100 percent), the probability of dense fog occurrence greatly increases. Such fogs can be triggered by the presence of only a relatively modest concentration of smoke. The LVORI can be used as a measure of the overall likelihood of smoke problems on a roadway, but must be considered with sightline estimates to evaluate **the** potential hazard of an individual fire.

Even in low humidity conditions, VSMOKE crossplume sightline estimates must be evaluated with care. The relationship between overall particulate matter concentrations and light scattering and extinction **coefficients** is subject to enough variation to cause errors in visual obscuration estimates of about a factor of 2. Therefore, a given VSMOKE visibility estimate could occur with associated overall particulate matter concentrations as little as one-half (or as much as 2) times the given value. Moreover, VSMOKE visibility estimates are dependent on the input contrast ratio criterion, CCOCRT. Under certain conditions, a small change in the input value of CCOCRT can result in a considerable change in the crossplume visibility estimate for a given downwind distance. For example, a smoke plume may be dense enough to reduce contrast to a value just above the criterion-i.e., an individual with eyesight matching the criterion will just be able to see through the plume. If the background atmosphere is very clean, objects beyond the plume will be dimly visible for a considerable distance beyond the plume boundaries. A less keen-eyed observer may not be quite able to see through the plume. A criterion contrast ratio set to match that observer's eyesight would result in a much lower visibility estimate.

The **VSMOKE** crossplume contrast ratio estimates are provided for two reasons. First, they are to alert the user to the sensitivity of visibility estimates. A contrast ratio estimate just above the criterion value should be weighted more heavily as a potential hazard indicator than an accompanying visibility estimate that falsely seems to provide an ample margin of safety. Second, roadway safety may be as comparably dependent on the ability to see the relevant portion of the roadway panorama clearly as the ability to dimly see an individual potential roadway hazard. In any case, the ability of the simple VSMOKE optical parameter calculations to characterize driving visibility appear limited, perhaps very limited at night. A conservative approach in specifying the input criteria for contrast ratio, CCOCRT, and visibility, VISCRT, and in interpreting the output visibility and contrast ratio tables is strongly recommended for all roadway-oriented VSMOKE applications.

The DI estimates from VSMOKE have a wider application than most of the other output. As an areawide, multiple-prescribed fire smoke management tool, DI represents an area source of about 3 1 by 3 1 miles (or roughly 1,000 square miles). However, it may be applied successfully to somewhat larger areas experiencing uniform weather conditions or to areas as small as 5 by 5 miles with little distortion in its description of the atmosphere's relative dispersive capacity. Dispersion Index does not apply to conditions within the plume of any one pollution source. Thus, DI should be used as a supplement to, not a substitute for, the single fire VSMOKE analysis.

The LVORI estimates from VSMOKE may be applied to either single or multiple fire air quality/traffic hazard management problems. Low Visibility Occurrence Risk Index is the only VSMOKE visibility analysis tool that can be currently applied without modification in humidities greater than or equal to 70 percent. However, LVORI should be used with caution until it can be corroborated by an independent data set, particularly in areas with a climatic regime significantly different from that of Florida.

Acknowledgments

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Appendix I—Input Hints

VSMOKE requires values for numerous input variables. Some are quite specialized, a few are unique to this model. In addition, VSMOKE estimates of concentration and visibility can be sensitive to input values, sometimes in ways not obvious to any but the most experienced users. Finally, some VSMOKE input variables are deliberately designed to allow running of multiple scenarios. This design allows for uncertainties in the scientific knowledge of fire behavior and chemistry, fire interaction with the atmosphere, dispersion and other meteorological processes, optics, and psycho-physical perception. These model characteristics dictate that considerable thought be given to determining input values. The following suggestions are not comprehensive but give the user a basis for determining appropriate input for and uses of VSMOKE.

In general: When the user believes a range of values is likely for any input variable, the sensitivity of VSMOKE output variables dictates that the user test for all extremes and representative mid-range values of each variable, thereby allowing the behavior of VSMOKE to be appropriately displayed.

Line 1 variable

NLPAGE: INTEGER. Number of lines per page of output, restricted to the range 60 to 66. Any value in this range that matches the host system parameters and restrictions may be used.

Line 2 variable

KTITLE: CHARACTER*72. The input value need not fill all 72 positions; any remaining positions trailing the input value are blank filled. This variable is purposely left open-ended, allowing adaptation to a wide range of filing or bookkeeping systems. Files VSMOKE.IPT, VSMOKE.SCR, and VSMOKE.OUT are intended to be used only as working files. The user who anticipates maintaining a library of input and output files should probably incorporate the library file name or other distinctive code within KTITLE to help identify and ensure the integrity of each file.

Input hints—Line 3 variables

ALAT, ALONG, TIMZON: REAL. In addition to allowing the program to determine stability class if needed, these variables serve a useful bookkeeping function. If VSMOKE is ever integrated into a system containing automated weather input data, these variables might be necessary to help determine local weather from a large data base. The user should be aware that limited error checking is performed on these variables. Because VSMOKE can be used at any location, including those with changing or unusual time zone conventions (e.g., near the international dateline or in areas with a fractional hour time zone), some values of ALONG and TIMZON that may appear erroneous at first glance are accepted into the program. The valid range for ALAT is -90.0 to +90.0; for ALONG, -240.0 to +240.0; and for TIMZON, -18.0 to +18.0.

IYEAR, MO, IDAY: INTEGER. Used in determining stability class if needed, these variables are also useful for bookkeeping purposes. No error checking is performed. Care should be taken to ensure consistency with input values of NPRIOD, HRSTRT, HRNTVL, and TFIRE. Like the location items, these variables may also be required if VSMOKE is integrated with a largerweather data base.

NPRIOD: **INTEGER.** Error checking is used to ensure a value from 1 to 100. A large value will result in longer execution times and a lengthier output file. Too small a value may result in missing the period of greatest fire impact.

HRSTRT: REAL. Input in decimal hours on a **24-hour** clock basis (e.g., **12:01** a.m. is **0.0167, 7:30** a.m. is **7.5, 2:45** p.m. is **14.75),** HRSTRT is referenced to and linked with **IYEAR,** MO, and **IDAY.** When NPRIOD is set to 1, the only analysis time is at HRSTRT. The values of **IYEAR,** MO, **IDAY, NPRIOD,** HRSTRT, HRNTVL, and **TFIRE** must be properly linked. No error checking is performed. Values should normally be within the range 0.0000 to 23.9999.

HRNTVL: REAL. Input in decimal hours, HRNTVL is added to HRSTRT for period 2, and added again for each subsequent NPRIOD. HRNTVL should be correctly linked with **IYEAR,** MO, **IDAY,** NPRIOD, HRSTRT, and **TFIRE.** HRNTVL should be small enough to allow analysis of the life cycle of the fire, smoke emissions, and weather conditions during each period of interest. Setting HRNTVL between 1 and 3 hours should yield satisfactory results from a meteorological standpoint for most prescribed fire situations in the Eastern United States. A shorter analysis interval (perhaps 0.1 hour) might be appropriate for short-lived or rapidly changing fires. HRNTVL is not used if NPRIOD is 1, although a value must be provided. For NPRIOD greater than 1, error checking ensures a value of at least 0.0001 hours (i.e., **5/18** seconds).

LSTBDY: LOGICAL. LSTBDY should be set to true only if stability class is included among the period-by-period data in the input file. The value of LSTBDY has little effect on VSMOKE run times.

LQREAD: LOGICAL. LQREAD should be set to true only if particulate matter and carbon monoxide emission rates, total sensible heat emission rate, and proportion of emissions subject to plume rise are included in the period-by-period data in the input file. The value of LQREAD has little effect on VSMOKE run times.

LSIGHT: LOGICAL. LSIGHT should be set to true whenever crossplume sightline estimates are required (i.e., when quantitative crossplume visibility and contrast ratio will be estimated). Setting LSIGHT to false when such estimates are not required can shorten run times by about a factor of 3.

CCOCRT: REAL. A value of 0.02 has been used for determining airport runway visual range, but this may be too low a contrast ratio for every licensed driver to recognize a hazard. Scattering of light may also prove to be more critical for night driving than for many situations faced by aircraft pilots. A value of at least 0.05 may be required, and some driving situations involving glare, various kinds of driver impairment, or both may require a much higher value, perhaps 0.25. An appropriate value of CCOCRT is best determined by specific research studies and consultation with such agencies as the National Highway Traffic Safety Administration. To allow for mathematical testing and unforeseen applications, VSMOKE permits a range of values from 0.000001 to 0.999999. Low values relate primarily to target identification; higher ones relate to the quality of view along the crossplume sightlines. The latter permits experimental use of VSMOKE for assessing smoke impact on scenic vistas. The user should ensure that the values of CCOCRT and VISCRT are in the proper relationship-acceptable visibility in VSMOKE is defined by maintenance of a contrast ratio of CCOCRT or more over a sightline length of at least VISCRT.

VISCRT: REAL. Values ranging from 10^{-7} miles (about 0.16 mm) to 9999.99 miles are permitted in VSMOKE. Much of this range should be reserved for mathematically exercising the model. VISCRT should ordinarily be related to specific traffic safety variables such as safe stopping distance. State traffic safety agencies often cite a criterion value of 500 feet (0.0947 miles). Other reasonable values might include 0.125, 0.25, 0.5, and 1 .O miles. Visual sightlines of more than a mile might be required in some cases, including aircraft operations. Protecting scenic vistas would typically require values of several to many miles. The user should ensure that the values of CCOCRT and VISCRT are in the proper relationship-acceptable visibility in VSMOKE is defined by maintenance of a contrast ratio of CCOCRT or more over a sightline length of at least VISCRT.

Input hints— Line 4 variables

ACRES: REAL. VSMOKE assumes a square area of smoke emissions, but generates a line source of length equal to the square root of ACRES at the downwind edge of the area. Implicitly, rotation of the area is performed by VSMOKE in case of wind shift. ACRES should ordinarily be equal to the area generating smoke emissions during the period of interest-generally equal to the area burned during a given fire. A lower value of ACRES may be necessary to account for "trouble spots" within a large burn area if smoke-sensitive receptors are close. With a lower value of ACRES, TONS (if LQREAD=FALSE) or EMTQPM, EMTQCO, and EMTQH (if LQREAD=TRUE) should also be reduced correspondingly, and the effects from the remainder of the burn area should be determined by adding the results of a second VSMOKE run. If the fire is to be evaluated as a point source, ACRES should be set to zero or a negative value. Point source modeling generally results in the most conservative estimates of centerline plume characteristics. Downwind concentration estimates close to a fire in VSMOKE are only moderately sensitive to ACRES and decrease with the square root of ACRES.

TONS: REAL. Defined as the total mass of fuel consumed by the fire within the complete burn area during the total period of analysis. TONS is used only if LQREAD is set to FALSE. If used, TONS must be non-negative. Past resources such as SFFLP (1976) generally used tons per acre to characterize fuel loading available for fire consumption. TONS is usually around three times ACRES for understory litter reduction burns. TONS can range as high as roughly 100 times ACRES for tracts with large piles of forest fuels.

EFPM: REAL. Documented particulate matter emission factors for southern forest fuels range from about 15 pounds per ton for dry, highly aerated fuel, such as grass, to as much as 200 pounds per ton for some poor combustion smoldering situations. The work of SFFLP (1976) was based on total suspended particulate matter (TSP), while the latest (1990) Clean Aii Act defines particulates by particle size. For most forestry smoke analysis, emission factors for TSP may be regarded as roughly equivalent to those for PM10 (i.e., particulate matter of diameter 10 micrometers (pm) or less). EFPM is used only if LQREAD is set to FALSE. If used, EFPM must be non-negative.

EFCO: REAL. Emission factors for carbon monoxide have been cited by SFFLP (1976) as ranging from 20 to 500 pounds per ton in southern forest fuels. Relative to the air quality standards in the Clean Air Act, carbon monoxide emissions are usually of secondary concern - PM10 standards will likely be broken before CO standards are approached. To illustrate, the current l-hour and 8-hour average CO NAAQS standards are nominally 40,000 and 10,000 $\mu g\ m^{-3}$, respectively; the current 24-hour average PM10 NAAQS standard is 150 $\mu g\ m^{-3}$. One exception is important: smoldering organic soils can emit very high amounts of CO and low amounts of particulates. Because organic soil combustion poses an extreme hazard, carbon monoxide analysis is provided in VSMOKE. EFCO is used only if LQREAD is set to FALSE. If used, EFCO must be non-negative.

TFIRE: REAL. Linked to IYEAR, MO, and IDAY, TFIRE (like HRSTRT) is input in decimal hours. The user should ensure that linkage between NPRIOD, HRSTRT, HRNTVL, and TFIRE is correct. The model simulation clock time for any given period is determined by the relationship, TSIM = HRSTRT + (IPRIOD - 1) * HRNTVL, where TSIM is current model time in decimal hours and IPRIOD is current model period under analysis, with IPRIOD ranging from 1 to NPRIOD. Any lack of precision in real arithmetic within the user's host system can cause unexpected results in the relationship between TSIM and TFIRE. The most striking of these occurs when TSIM is calculated to be just less than TFIRE while the user is expecting an exact match. For example, HRSTRT = 11 .O, HRNTVL = 1.0, NPRIOD = 3, and TFIRE = 12.0 may result in concentration estimates for the last period only, because TSIM could be internally represented as 11.999... during IPRIOD = 2, when a value of 12.0 is intended. This problem did not occur when VSMOKE was run in environments that used the 80387 math co-processor or equivalent; however the problem has occurred on other systems. A small margin (perhaps 0.0001 hours) should be built info the input value of HRSTRT or TFIRE if this problem is encountered or anticipated.

THOT: REAL. Input in decimal hours, THOT expresses the duration of the period beginning at time, TFIRE, when the heat of the fire causes an active convection column with significant plume rise for a substantial proportion of emissions. After time, TSIM = TFIRE + THOT, any continuing emissions of the fire are restricted to ground-level-based dispersion. For lines of fire, an estimate of THOT may be obtained by dividing the rate of spread into the distance that the line of fire must cover. For piled debris fires, THOT should probably be used to characterize the period of active flaming while RFRC or EMTQR should be used to help characterize any period when the appearance of the smoke column indicates both flaming and smoldering processes. Slight mathematical processor errors in model time calculations can cause unexpected results in some systems. This problem occurs if the calculated model time, TSIM, causes a given period to be just inside or outside of the convective period when the opposite result is expected. THOT is used only if LQREAD is set to FALSE. If used, THOT must be non-negative and less than TCONST.

TCONST: REAL. Input in decimal hours, TCONST expresses the duration of the period, beginning at time TFIRE, when the total emission rate of the fire may be regarded as constant. For lines of fire, TCONST will probably be equal to or slightly greater than THOT. For piled debris, emissions from smoldering can be high enough to cause TCONST to exceed THOT by a substantial amount (Lavdas 1982). Slight mathematical processor errors in model time calculations can cause unexpected results in some systems. This problem is most likely to cause substantial errors at the end of the period of constant emissions and could be significant for a given period if TDECAY is set to zero or is much smaller than HRNTVL. TCONST is used only if LQREAD is set to FALSE. If used, TCONST must be non-negative and greater than or equal to THOT; also, TCONST + TDECAY must exceed zero.

TDECAY: REAL. Input in decimal hours, TDECAY expresses the decay constant for exponential decay of total emission rate of the fire, beginning at time, TBGDCY = TFIRE + TCONST. Emission rate at any time at and after TBGDCY is expressed as: ERDCAY' = ERPEAK * exp (-(TSIM - TBGDCY) / TDECAY), where ERPEAK is the "peak" emission rate of the fire which occurs at time TBGDCY, and TSIM is the current model time in decimal hours. For each TDECAY hours after time = TFIRE + TCONST, the total emission rate of the fire is reduced by a factor of e (becomes about 0.37 of its value at the start of the TDECAY period). TDECAY is closely related to the concept of "half-life." The half-life of emissions after time = TBGDCY is about 0.693 * TDECAY. TDECAY is probably no more than 1 hour (and can be much less) for light fuels such as pine needles, grass, and low brush. In aggregate, TDECAY has been found to be about 4 hours for burning activity near the Willamette Valley, Oregon in the late 1970's (Lavdas 1982). For organic soils, TDECAY can be large enough to make the decay concept moot. Such a fire is better characterized by daily runs of VSMOKE that assume constant emissions for each day. TDECAY is used only if LQREAD is set to FALSE. If used, TDECAY must be non-negative and TCONST + TDECAY must exceed zero.

LGRISE: LOGICAL. LGRISE should be set to true in most cases. Setting it to false can cause underestimates of plume impact near the fire. This setting causes immediate attainment of final plume height, and is useful primarily when comparing VSMOKE results with models that do not use gradual plume rise, such as INPUFF, version 2.0 (Petersen and Lavdas 1986). LGRISE has little effect on run time.

RFRC: REAL. This is a rather complex and unique variable, with acceptable input range from - 1.0 to + 1.0. The absolute value of RFRC expresses the proportion of emissions subject to plume rise. A positive value places the plume rise proportion at the Briggs (1975) plume height for each calculated downwind distance in the model; a negative value uniformly distributes the smoke from the ground to the Briggs plume height. The remaining proportion is placed at the ground. A value of + 1.0 or - 1.0 means all smoke is subject to plume rise; a value of 0.0 means no smoke rises. Once the distribution due to RFRC is set, both proportions are subject to initial dispersion (as input) and transport-related dispersion processes. By using a positive input value, RFRC accommodates the concept of "split plume rise" discussed in SFFLP (1976) and Lavdas (1978). Setting RFRC to 0.6 causes VSMOKE to conform to the assumptions given by SFFLP (1976). Setting RFRC to 1.0 causes complete plume rise, allowing VSMOKE to conform to industrial stack oriented models such as CRSTER (U.S. EPA 1977). A value of zero inhibits all plume rise, resulting in very conservative estimates of plume impact. Negative values of RFRC activate the initially vertically uniformly distributed approach, which implies that the smoke forms a uniform "curtain" from ground to plume height, and any remaining smoke is dispersed from ground level. For low intensity prescribed forest fires, as described by Lavdas (1978), either + 0.60 or - 0.75 is suggested for RFRC. The -0.75 value is based on an unpublished reanalysis of aircraft data (Lavdas 1978) which resulted in a slight improvement in concentration estimates nearest the ground and a considerably better match to the observed vertical smoke profiles. RFRC is used only if LQREAD is set to FALSE.

Input hints—Meteorological period-by-period variables

Unless otherwise indicated, each of these variables is stored in arrays:

NUMDWX: INTEGER. Neither stored in an array nor otherwise used after it is read into VSMOKE, NUMDWX helps in bookkeeping the weather input data. Only the host-system-dependent limitations for a list-directed read of an integer variable constrain its use. One convenient approach involves specifying date and time for the weather data that follows on the same line, e.g., NUMDWX = 19970715 16 signifies 16 hours, 15 July 1997. The year-month-date-hour order is convenient when mathematical sorting is used to construct the data set.

TTA, PPA: REAL. These variables are used in VSMOKE only to perform mathematical operations between carbon monoxide emissions and concentrations. If CO concentrations are not significant, default values may be forced by inputting a value less than - 459.0 F for TTA and less than 0.1 mb for PPA. For PPA, the actual (i.e. station) pressure rather than sea level pressure should be used.

IRHA: INTEGER. This variable must be determined from weather observations or forecasts applicable for the time and place of analysis. Values from 0 to 100 are accepted by the program. Because relative humidity is used to determine other variables in an array "look up" sense, to maintain conservative "worst-case" estimates, any fractional value of relative humidity should be automatically rounded up (e.g., 48.23 percent should be input as 49). If variations in RH are expected within the smoke impact area or during the time period represented, the "worst-case" (i.e., highest) RH should be used.

LTOFDY: LOGICAL. This variable **defines** "day" vs. "night" for a given period. VSMOKE defines "day" as the period commencing just after sunrise and terminating just before sunset. All other times are defined as "night." Unlike most published sunrise and sunset times, the apparent solar disk radius and effects of atmospheric refraction are not considered in VSMOKE. Therefore, VSMOKE solar ephemeris determinations result in a slightly shorter daylength for a given date and location than most **almanacs.** Although the value of LTOFDY can critically affect VSMOKE output, such large model output differences may be triggered by data that reflect rather trivial differences in actual physical conditions. These VSMOKE sensitivities demonstrate the need to use the model in the most conservative sense reasonable for a given situation. In general, VSMOKE analysis should be extended into a period that the model regards as "night" if there is any indication that smoke could cause a potential problem from a little before sunset to a little after sunrise. LTOFDY is read and used in VSMOKE only if LSTBDY is set to TRUE.

ISTABA: INTEGER. With acceptable values from 1 to 7, this variable characterizes stability class. Lavdas (1986) or Turner (1964) should be consulted if there is any question about determining or interpreting stability class. If stability class cannot be provided, the user should automatically estimate stability class (achieved by setting LSTBDY to false). VSMOKE output is rather sensitive to stability class in many situations, and the discrete nature of the stability classification system used in VSMOKE causes some "jumpiness" in model output results. Therefore, a conservative approach is suggested that accounts for the effects of both adjacent classes on smoke concentration estimates for sample burns. For example, if three is input, the effects of using two and four as inputs for the given burn geometry and dispersion situation should be known. ISTABA is read and used only if LSTBDY is set to TRUE.

WSSFC, **ICOVER,** CEIL: REAL, INTEGER, REAL. Not stored in arrays, these variables are based on surface weather observations. They are read and used only if LSTBDY is set to FALSE. The "jumpy" response of VSMOKE with respect to stability class can be triggered by small shifts in any of these three surface weather variables. A conservative approach, such as "forcing" a more stable class in a borderline case, is strongly recommended. **ICOVER** is restricted to the range 0 to 10; WSSFC and CEIL must be non-negative.

AMIXA: REAL. Under near neutral or unstable conditions, the interpretation of mixing height is straightforward. Mixing height can be estimated by (and usually requires) a meteorologist (or well-designed and tested meteorological software package) with access to upper air and surface weather data. The meteorologist should note that VSMOKE retains the mixing height concept even under stable conditions when mixing height, in a thermodynamic sense, no longer exists (or might be said to equal zero). VSMOKE treats mixing height as an impenetrable "lid" that perfectly traps all smoke. Specifying too low a mixing height will result in unrealistically high smoke concentration and visibility impact because smoke in an inversion layer slowly disperses within the layer. In stable conditions, AMIXA values should be set to at least 100 m. These values may be set lower if a good reason, such as well defined subsidence, exists, However, the VSMOKE dispersion coefficients are not designed to account for important dispersion effects when an inversion is extremely close to the surface. Because mixing height when used to determine DI at night is restricted to the range between 240 and 600 m, restricting the VSMOKE input for AMIXA in "night" conditions to this range is generally prudent. However, to allow for testing VSMOKE mathematical performance on varying host computer systems, any value of 1 .0 m to 10,000.0 m is accepted by the program.

UA: REAL. This variable also requires a meteorologist (or appropriate software package) with access to surface and upper air weather data. UA is the average (or "net") windspeed for the layer of atmosphere within which significant smoke concentrations from the fire occur and are likely to affect roadways and other sensitive areas. Extra weight should be given to surface wind observations or forecasts, especially in the presence of a surface inversion. Dense layers of smoke near the ground in stable conditions are most likely to cause traffic hazards. A reasonable practice is to weigh the surface windspeed equally with the average of speeds aloft within any actual or assumed mixing (or smoke) layer. In operational conditions where the available surface data are more likely to be representative of conditions at the time and place of analysis than are the upper air data, the surface report may be given precedence when it exceeds the "raw" transport windspeed value. For example, if a remote morning raob is used to determine a transport windspeed of 4.0 meters per second (m/s), and an afternoon observation gives a surface windspeed of 10 knots, and that surface wind is regarded as representative of conditions in and near the burn area, then the appropriate value of UA would be no less than 10 knots, or about 5.1 m/s. UA must be at least 0.1 m/s.

OYINTA, OZINTA: REAL. These variables allow period-by-period input of "initial" dispersion in the horizontal (OYINTA) and vertical (OZINTA) crossplume directions. Any non-negative value is acceptable. The most conservative approach for estimating concentrations from ground-level smoke is to use zero for both OYINTA and OZINTA. This approach corresponds to the practice of SFFLP (1976). The most conservative approach for fires with complete plume rise (RFRC or EMTQR = + 1 .0) is to input the highest reasonable value for OZINTA and zero for OYINTA. Rigorously determining appropriate non-zero values requires rather sophisticated monitoring of smoke behavior near fires. Appropriate data are generally lacking. Selecting appropriate values in an operational environment requires a knowledge of the initial distribution and virtual distance concept as used in VSMOKE. A Gaussian distribution of pollutants is applied at the source due to these coefficients. Downwind calculations are handled by adding virtual distances to the source/receptor relationships. These must be equivalent to those necessary to generate the specified initial distributions from a point source by transport-related model dispersion processes. Other VSMOKE input variables also describe the geometric configuration of a ground fire as a pollution source. Both OYINTA and ACRES (the square root of which is the effective line length of the source) help specify horizontal distribution of smoke at the source, while both **OZINTA** and RFRC (or EMTQR, if LQREAD is true) help specify vertical distribution of smoke at the source. The net "initial" distribution resulting from the effect of all VSMOKE input values should reasonably represent the geometry of the smoke source analyzed:

BKGPMA: REAL. This is a "generic" background period-by-period concentration for particulate matter in micrograms per cubic meter **($\mu g\ m^{-3}$).** Generally, the PM10 fraction, as defined by the 1990 Clean Air Act (unless and until superseded) should be used if available. In any case, BKGPMA should correspond to the particular matter component specified for EFPM (if **LQREAD=FALSE)** or for EMTQPM (if LQREAD=TRUE). For the foreseeable future, little or no monitoring of particulate matter is likely to be available at most prescribed burn field locations, therefore a **value** for BKGPMA will usually be assumed. The input value must be non-negative; a zero input causes VSMOKE to determine smoke concentrations only from the single fire under analysis. When **LSIGHT** is set to TRUE, a zero value for BKGPMA leads to unrealistic **crossplume** sightline estimates. If background visibility is the only basis for BKGPMA, the following relationship should be **used:**

$$BKGPMA = 3.0E{+}05\left(\frac{2.431E{-}03}{VISM} - 1.5E{-}05\right)$$

where

VISM is the background visibility in miles. For example, VISM = 1 mile, BKGPMA = 725 $\mu g\ m^{-3}$; VISM = 7 miles, BKGPMA = 100 $\mu g\ m^{-3}$.

BKGCOA: REAL. This is period-by-period background concentration for carbon monoxide in parts per million based on a density of CO per total density of air. Little or no monitoring data are likely to be available in most prescribed burn situations. The input value must be non- negative; a zero input yields smoke concentrations from only the single fire under analysis without adverse effects on subsequent model calculations. Unlike particulate matter concentrations, VSMOKE CO concentration estimates are influenced by input values of ambient temperature, pressure, and moisture.

Input hints—Emissions related period-by-period variables

Note: These variables are read and used by VSMOKE only if LQREAD is set to TRUE, which indicates that period-by-period emissions related data are included in the input file.

NUMDRT: INTEGER. This variable serves a "bookkeeping only" function with respect to the optional period-by-period emission rate related data. Any bookkeeping system within the limitations of the user's host system may be used. NUMDRT is not stored in an array or used in any other capacity.

EMTQPM, EMTQCO: REAL. These variables would ordinarily be derived **from** an emissions model for a prescribed fire. Both the particulate matter (EMTQPM) and carbon monoxide **(EMTQCO)** emission rates in grams per second represent the total fire for the given period. Any non-negative value for either emission rate is acceptable. Because the values can be high, the use of the powers of 10 format (e.g., **1.5E+06** for **1,500,000)** may be more convenient and allow more exact representation of the input values of EMTQPM and EMTQCO within VSMOKE. The current version of VSMOKE treats particulate matter "generically"; that is, emissions and concentrations may be for total particulate matter or for **particulates** within a given size class. Whichever component of particulate matter is used in a given VSMOKE run, the input value(s) of EMTQPM should match the component described by the input value(s) of BKGPMA.

EMTQH: REAL,. This variable would probably be derived **from** a model of a prescribed fire that tracks and outputs either sensible heat emission rate or the rate of mass loss of fuel. This variable is available **from** some emission models for prescribed tire (Sandberg and Peterson 1984). As of December 3 **1, 1991,** heat emission estimates from this model (i.e., the ERM model) were given in BTU's per second and must be converted to megawatts (by multiplying by 1.0551 * 10") before running in VSMOKE. EMTQH can be estimated **from** a knowledge of the rate of fuel consumption and the amount of sensible heat released to the atmosphere per unit mass of fuel consumed. Fuel consumption rate estimates are available within some emissions models, while sensible heat release per unit fuel can be assumed constant for many forest fuels. Any non-negative value is acceptable. Using powers of 10 notation may prove more convenient and allow more exact representation of EMTQH within VSMOKE.

EMTQR: REAL,. This variable may be regarded as a period-by-period value of RFRC. The absolute value of EMTQR specifies the proportion of smoke emissions subject to plume rise. The sign of EMTQR specifies the initial vertical distribution assigned to the plume rise associated smoke. If positive, all plume rise smoke is dispersed from the calculated plume height; if negative, the plume rise smoke is initially uniformly distributed from the ground to the calculated plume height. In either case, all remaining smoke is dispersed from the ground. EMTQR is more specialized than the three preceding emissions values, and may not be available **from** emissions model output. If no data are available, the best available estimate of RFRC for the active combustion period should be used for each period with significant active flaming combustion. When heat emissions become low and the source of heat is widespread (e.g., smoldering smoke sources scattered throughout the burn area), setting **EMTQR** to zero yields the most conservative estimates of smoke impact. Values from - 1.0 to + 1.0 are **accepted** by the program. SFFLP **(1976),** in effect, assigned a value of + 0.6 to EMTQR during the "convective **lift** phase" of a fire, and 0.0 during the "no convective **lift** phase." Either a value of-t 0.60 or - 0.75 can be justified **from** the low-intensity prescribed fire and smoke data analyzed by **Lavdas (1978),** and - 0.75 may be a better value, according to an unpublished analysis.

Appendix II—Input Examples

The following examples are for illustration only and should not be construed as recommendations for input values.

Example 1—A quick check of day and night smoke conditions

It is March **15, 1996.** A burn is scheduled to begin tomorrow **afternoon** at 2 p.m., on the Fictitious National Forest in South Carolina. The location of the burn site is 33.6" N. 79.7' W. The burn is a **40-acre** series of backfires that will reduce the **fuel** loading by 2.5 tons per acre. No emission rate data **from** modeling efforts are available, but consultations with experts indicate that the emission factor for **particulates** is 30 pounds per ton, the duration of both the convective and constant emissions period of the fire is 2.5 hours, the appropriate value of the exponential decay constant is 0.5 hours; 75 percent of the smoke will rise to **full** plume height and 25 percent will remain on the ground. For this burn, carbon monoxide concentrations are not needed, but crossplume visibility estimates are-a contrast ratio of 0.10 or better is desired at a distance of **1/8** mile. The smoke plume undergoes gradual rise. The weather forecast specifies tomorrow's stability class to be 3, mixing height of 1200 m, and transport windspeed of 7.0 m/s. The following evening, a stability class of 6 and transport windspeed of 2.5 m/s are expected, and an appropriate mixing height input would be 300 m. Predicted RH is 45 percent for tomorrow **afternoon,** rising to 80 percent by 8 p.m., and 95 percent by 2 a.m. the next day. The horizontal and vertical "initial" dispersion coefficients are to be set to zero throughout the life of the fire. The background concentration of particulate matter will be 40 $\mu g\ m^{-3}$ throughout the period. The **VSMOKE.IPT** file should contain the following information:

NLPAGE - 66, appropriate for uncontrolled form fold line printers
KTITLE - one can simply use the title of example 1; a **numbering system** enclosed in apostrophes could be devised for operational use
ALAT - 33.6" N
ALONG - **79.7"** W
TIMZON - in March in South Carolina would be EST, or 5.0 hours behind UTC
IYEAR - 1996
MO - March, or 3
IDAY - 16
NPRIOD - estimates for 2 p.m., 8 p.m., and 2 a.m. are desired; use 3
HRSTRT - use the fire start time; on a **24-hour** decimal clock, 2 p.m. is 14.0
HRNTVL - the desired estimate times are every 6 hours, use 6.0
LSTBDY - stability classes are a part of the input forecast; use T
LQREAD - no period-by-period emission rate related data are available; **use F**
LSIGHT - crossplume sightline estimates are desired; use T
CCOCRT - 0.10
VISCRT - 0.125
ACRES - 40.0

TONS - 100.0 (2.5 tons per acre times 40 acres)
EFPM - 30.0
EFCO - carbon monoxide analysis is not needed; use 0.0
TFIRE - 2 p.m.; use 14.0,
THOT - 2.5
TCONST - 2.5
TDECAY - 0.5
LGRISE - gradual plume rise calculation is desired, use T
RFRC - 75 percent of smoke rises fully and disperses from full plume height; use 0.75
NUMDWX - this particular user finds the numbers 14, 20, and 26 to be the most convenient way to keep track of times associated with the weather data; a more robust method would be 199603 16 14, 199603 1620, and 199603 1702
TTA - used only in determining CO concentrations in parts per million; a default is forced
, PPA - used only in determining CO concentrations in parts per million; a default is forced
IRHA - relative humidities are 45, 80, and 95 percent
LTOFDY - 2 p.m. is day, 8 p.m. is after sunset, and 2 a.m. is night; use T,F,andF
ISTABA - stability classes are 3, 6, and 6
AMIXA - mixing heights are 1200., 300., and 300. m
UA - transport windspeeds are 7.0, 2.5, and 2.5 m/s
OYINTA - "initial" horizontal dispersion coefficients are 0.0, 0.0, and 0.0
OZINTA - "initial" vertical dispersion coefficients are 0.0, 0.0, and 0.0
BKGPMA - background particulate matter concentrations are 40 $\mu g\ m^{-3}$ for all periods, use 40.0, 40.0, and 40.0
BKGCOA - carbon monoxide is not considered in this example; zeros can be used

The VSMOKE.IPT file for example 1 should appear as follows:

```
66
'EXAMPLE 1 - A QUICK CHECK OF DAY AND NIGHT SMOKE
CONDITIONS'
33.6 79.7 5.0 1996 3 16 3 14.0 6.0 T F T 0.10 0.125
40.0 100.0 30.0 0.0 14.0 2.5 2.5 0.5 T 0.75
14 -500. -1. 45 T 3 1200.7.0 0.0 0.0 40.0 0.0
20 -500. -1. 80 F 6 300.2.5 0.0 0.0 40.0 0.0
26 -500. -1. 95 F 6 300.2.5 0.0 0.0 40.0 0.0
```

Example 2A and 2B—A more detailed look at a head fire at the same site

Same time, same place, different firing technique. A head fire takes less time to burn through the site (assume 1.75 hours); the experts say that the emission factor should be 60 pounds per ton, the constant emission period outlasts the convective period by a half hour, the decay constant should be "doubled, maybe tripled," and 75 percent of smoke that rises will be uniformly distributed between the ground and **the** predicted plume height. No one has much to say about "initial" dispersion coefficients. The user decides hour-by-hour estimates of smoke concentrations and crossplume visibilities are needed and consults with a meteorologist about hourly weather input. The user is advised that "procedure 1" is acceptable. Assume this uses the afternoon weather between noon and 2 hours before sunset and linearly interpolates relative humidity and stability class to evening and late night values. The night values of transport windspeed and mixing height are used all night. After sunrise, the stability class rises one class per hour to a daytime value of 4 or less, but mixing height and transport windspeed lag behind until midmorning. In the operational world, a little program **already** exists that handles this **weather** data generation automatically. The "initial" dispersion coefficients are handled by setting them to zero (generally the most conservative course of action, unless better information is available). Because the "doubled or maybe tripled" decay constant is vague, you decide to run the program twice. The **VSMOKE.IPT** for the **first** run should contain the following information:

NLPAGE - assume a system setup makes 63 most convenient
KTITLE - merely need to distinguish between the two cases
ALAT, ALONG, TIMZON, **IYEAR,** MO, **IDAY -** same as example 1
NPRIOD - continue until 8 a.m. the following day; use 19
HRSTRT - use the start time for the fire, 14.0
HRNTVL - 1.0
LSTBDY, LQREAD, LSIGHT, CCOCRT, VISCRT - same as example 1
ACRES, TONS - same as example 1
EFPM - 60.0
EFCO, **TFIRE -** same as example 1
THOT - 1.75
TCONST - half an hour longer than THOT, or 2.25
TDECAY - "doubling" example 1 gives 1.0
LGRISE - still desired, use T
RFRC - 75 percent of smoke rises resulting in a uniform vertical distribution; use -0.75
NUMDWX - choose 14-23, then 00-08
TTA, PPA - use defaults, same as example 1
IRHA - use 45 from 2 p.m. to 5 p.m., then work upward to 80 and 95 percent
LTOFDY - sunrise is **6:20** a.m., sunset is **6:20** p.m.
ISTABA - keep 3 from 2 p.m. to 5 p.m., go up 1 per hour until 8 p.m., hold to 6 a.m., then use 5 for 7 a.m., 4 for 8 a.m.
AMIXA - 1200. m through 6 p.m., then 300. m
UA - 7.0 **m/s** through 6 p.m., **then** 2.5 **m/s**
OYINTA, OZINTA, BKGPMA, and BKGCOA - same as example **1**

The VSMOKE.IPT file for example 2A should appear as follows:

```
63
'EXAMPLE 2A - A DETAILED HEAD FIRE ANALYSIS WITH TDECAY = 1.0
HOURS'
33.6 79.7 5.0 1996 3 16 19 14.0 1.0 T F T 0.10 0.125
40.0 100.0 60.0 0.0 14.0 1.75 2.25 1.0 T -0.75
14 -500. -1. 45 T 3 1200.7.0 0.0 0.0 40.0 0.0
15 -500. -1. 45 T 3 1200.7.0 0.0 0.0 40.0 0.0
16 -500. -1. 45 T 3 1200.7.0 0.0 0.0 40.0 0.0
17 -500. -1. 45 T 3 1200.7.0 0.0 0.0 40.0 0.0
18 -500. -1. 57 T 4 1200.7.0 0.0 0.0 40.0 0.0
19 -500. -1. 69 F 5  300.2.5 0.0 0.0 40.0 0.0
20 -500. -1. 80 F6   300.2.5 0.00.040.00.0
21 -500. -1. 83 F 6  300.2.5 0.0 0.0 40.0 0.0
22 -500. -1. 85 F 6  300.2.5 0.0 0.0 40.0 0.0
23 -500. -1. 88 F 6  300.2.5 0.0 0.0 40.0 0.0
00 -500. -1. 90 F 6  300.2.5 0.0 0.0 40.0 0.0
01 -500. -1. 93 F 6  300. 2.5 0.0 0.0 40.0 0.0
02 -500. -1. 95 F 6  300.2.5 0.0 0.0 40.0 0.0
03 -500. -1. 95 F 6  300.2.5 0.0 0.0 40.0 0.0
04 -500. -1. 95 F 6  300.2.5 0.0 0.0 40.0 0.0
05 -500. -1. 95 F6   300.2.5  0.0  0.040.00.0
06 -500. -1. 95 F 6  300.2.5 0.0 0.0 40.0 0.0
07 -500. -1. 95 T 5  300.2.5 0.0 0.0 40.0 0.0
08 -500. -1. 95 T 4  300.2.5 0.0 0.0 40.0 0.0
```

The run for example 2B changes only KTITLE and TDECAY (from 1 .O to 1.5):

```
63
'EXAMPLE 2B - A DETAILED HEAD FIRE ANALYSIS WITH TDECAY = 1.5
HOURS'
33.6 79.7 5.0 1996 3 16 19 14.0 1.0 T F T 0.10 0.125
40.0 100.0 60.0 0.0 14.0 1.75 2.25 1.5 T -0.75
14 -500. -1. 45 T 3 1200.7.0 0.0 0.0 40.0 0.0
15 -500. -1. 45 T 3 1200.7.0 0.0 0.0 40.0 0.0
16 -500. -1. 45 T 3 1200. 7.0 0.0 0.0 40.0 0.0
17 -500. -1. 45 T 3 1200.7.0 0.0 0.0 40.0 0.0
18 -500. -1. 57 T 4 1200.7.0 0.0 0.0 40.0 0.0
19 -500. -1. 69 F 5  300. 2.5 0.0 0.0 40.0 0.0
20 -500. -1. 80 F 6  300.2.5 0.0 0.0 40.0 0.0
21 -500. -1. 83 F 6  300.2.5 0.0 0.0 40.0 0.0
22 -500. -1. 85 F 6  300.2.5 0.0 0.0 40.0 0.0
23 -500. -1. 88 F 6  300.2.5 0.0 0.0 40.0 0.0
00 -500. -1. 90 F 6  300. 2.5 0.0 0.0 40.0 0.0
01 -500. -1. 93 F 6  300.2.5 0.0 0.0 40.0 0.0
02 -500. -1. 95 F 6  300.2.5 0.0 0.0 40.0 0.0
03 -500. -1. 95 F 6  300.2.5 0.0 0.0 40.0 0.0
```

```
04 -500. -1. 95 F 6   300.2.5  0.0 0.0 40.0 0.0
05 -500. -1. 95 F 6   300.2.5  0.0 0.0 40.0 0.0
06 -500. -1. 95 F 6   300.2.5  0.0 0.0 40.0 0.0
07 -500. -1. 95 T 5   300.2.5  0.0 0.0 40.0 0.0
08 -500. -1. 95 T 4   300.2.5  0.0 0.0 40.0 0.0
```

Example 3—Forecast stablllty class unknown

Assume the same conditions as example 1, except stability class is not given in the forecast and crossplume visibility estimates are not required. The weather forecast is given as "clear tomorrow, with winds of 10 mph; fair tomorrow night with winds of 5 mph." For this example, **VSMOKE.IPT** should contain the following information:

NLPAGE - set to the minimum of 60 lines per page
KTITLE - use the above title
ALAT through HRNTVL - same as example 1
LSTBDY - stability class not available; use F
LQREAD - period-by-period emission rate related data not available; **use F**
LSIGHT - crossplume sightline estimates not **required;** use F
CCOCRT, VISCRT - same as example 1
ACRES through RFRC - same as example 1
NUMDWX - although weather format is for LSTBDY = F, this is same as example 1
IRHA - **same** as example 1
WSSFC - 10 mph tomorrow, 5 mph tomorrow night; 'these convert to 8.6 and 4.3 knots; use **8.6, 4.3,** and 4.3 (the 5 mph forecast applies to both 8 p.m. and 2 a.m.)
ICOVER - clear is 0 tenths, fair is generally under 5 tenths, the exact number within the 0 to 4 range is not critical; use 0, 0, and 0
CEIL - there is no ceiling unless **ICOVER** is 6 or more; use 99999. for all **three periods**
AMIXA, UA, **OYINTA, OZINTA,** BKGPMA and BKGCOA - same as example 1

The **VSMOKE.IPT** file for example 3 should appear as follows:

```
60
EXAMPLE 3 - FORECAST STABILITY CLASS UNKNOWN:'
33.6 79.7 5.0 1996 3 16 3 14.0 6.0 F F F 0.10 0.125
40.0 100.0 30.0 0.0 14.0 2.5 2.5 0.5 T 0.75
14 -500. -1. 45 8.6 0 99999. 1200.7.0 0.0 0.0 40.0 0.0
20 -500. -1. 80 4.3 0 99999.  300.2.5 0.0 0.0 40.0 0.0
26 -500. -1. 95 4.3 0 99999.  300.2.5 0.0 0.0 40.0 0.0
```

Example 4—Example 3 with clouds

Assume now the same conditions as example 3, except the forecast is cloudy conditions tomorrow and tomorrow night. After consulting a meteorologist, you find that ICOVER inputs should be 6, 9, and 10, and CEIL inputs should be 12000., 6000., and 3000. VSMOKE.IPT for example 4 should appear as follows:

```
60
'EXAMPLE 4 • FORECAST STABILITY CLASS UNKNOWN, CLOUDS IN
FORECAST:'
33.6 79.7 5.0 1996 3 16 3 14.0 6.0 F F F 0.10 0.125
40.0 100.0 30.0 0.0 14.0 2.5 2.5 0.5 T 0.75
14 -500. -1. 45 8.6 6 12000. 1200.7.0 0.0 0.0 40.0 0.0
20-500. -1. 804.3 9 6000. 300.2.50.00.040.00.0
26 -500. -1. 95 4.3 10 3000. 300.2.5 0.0 0.0 40.0 0.0
```

Example S-Smoldering organic soils scenario with convoys available

Generally, carbon monoxide concentrations from a prescribed fire tend to be less critical than particulate matter. Carbon monoxide is invisible and does not directly affect visibility. Moreover, air quality emission factor compilations (U.S. EPA 1985, 1988, 1990) set typical emission factors for CO relatively low compared to particulate matter with respect to air quality standards. An exception can occur when dealing with smoldering organic soils. These fires may often be relatively "clean" with respect to particulates, but "dirty" with respect to CO. Smoldering organic soil is a situation that should be absolutely avoided in prescribed burning operations. These emissions can last for weeks; the combustion is virtually impossible to extinguish unless environmental conditions are unusually favorable, and the resulting smoke is both inherently dangerous for traffic safety and potentially highly damaging to general air quality. When used with care, VSMOKE can be applied for any ground-based emissions source, including a fire in organic soil caused by a lightning strike. VSMOKE can be used to obtain a "snapshot" of atmospheric conditions during poor weather when the likelihood of safety problems is greatest. For this example, the fire has been ongoing as a smoldering source for several weeks. Assume that law enforcement officials are actively involved in convoying traffic through affected roadways. Please note that consultations with experts are required for these conditions. The following input represents a hypothetical situation used for illustration only.

Elements in example 5 that may require clarification are:

ALAT, ALONG • have been moved to an area containing deep organic soils

TIMZON, IYEAR, MO, IDAY • changed to late summer; note daylight savings time

NPRIOD, HRSTRT, HRNTVL • this is a scenario snapshot; only the 4 a.m. conditions are of interest; HRNTVL is not used

CCOCRT - assume that consultation with law enforcement officials have resulted in an agreement to set the value to 0.02; patrols will lead all traffic through the area in low-speed convoys

VISCRT - set by consultation, convoys will be run at low speeds, with 500 foot (0.0947 mile) visibility regarded as adequate

ACRES - assumed to be 40.0, but many organic soils fires are much larger

TONS - note that the tons per acre consumed during the snapshot period is low, only 0.1; this fuel is consumed during the period specified by the sum of TCONST and TDECAY

EFPM, EFCO - reflect the "clean" and "dirty" nature of the source with respect to particulate matter and carbon monoxide

TFIRE - specified as 3:30 a.m.; this means only that the source emissions are "underway" when the model concentrations are calculated at 4 a.m.

THOT - the source is "cool"; THOT is specified as zero

TCONST, TDECAY - the smoldering soils are assumed to be in a "steady-state"; for the purposes of the snapshot, TCONST is set to 1 .O hour and TDECAY to 0.0; that is, 0.1 tons per acre (4 tons in the 40 acres) of fuel are consumed in the 1 hour specified by TCONST + TDECAY

RFRC - a cool source is assumed; RFRC is set to zero, but is not used

NUMDWX - a year/month/day/hour integer is used in this case

IRHA though UA - reflect very poor atmospheric dispersion conditions

OYINTA, OZINTA - assume these nonzero quantities are given by an expert; although OYINTA in this case is of limited practical importance, the nonzero OZINTA value acts to slightly reduce concentrations close to the source

BKGPMA, BKGCOA - assume that 75 $\mu g\ m^{-3}$ for particulates and 6.0 ppm for CO have been monitored as background levels

The VSMOKE.IPT file for example 5 should appear as follows:

```
66
EXAMPLE 5 - SMOLDERING ORGANIC SOILS SCENARIO WITH
CONVOYS AVAILABLE:'
34.6 77.9 4.0 1997 8 22 1 4.0 0.0 T F T 0.02 0.0947
40.0 4.0 10.0 1000.0 3.5 0.0 1.0 0.0 T 0.0
1997082204 72.0 1012.5 100 F 7 240. 1.0 5.0 5.0 75.0 6.0
```

Example 6—Example 5 with emission rate estimates available

Close monitoring of smoke from prescribed fires that permits rigorous estimates of the emissions input requirements of VSMOKE under the LQREAD = TRUE option may not occur in the near future. However, the problems associated with the persistent smoke from burning organic soils may soon result in close monitoring of these types of fires. Progress in smoke models generating the necessary input data may also continue, e.g., work continues on such efforts pioneered by Sandberg and Peterson (1984). To illustrate the LQREAD = TRUE option, assume that the smoldering fire in example 5 has continued for an additional week: during that time, its emission rates have been well established. The input elements in example 6 follow:

KTITLE - 'EXAMPLE 6 - SMOLDERING ORGANIC SOILS WITH KNOWN EMISSION RATES:'

ALAT, ALONG, **TIMZON** - same as example 5

WEAR, MO, **IDAY** - one week later, i.e., 1997 8 29

NPRIOD - assume three snapshot analyses are to be performed with worst-case meteorology and three different emissions scenarios developed **from** the monitoring program; this procedure is an artifact used instead of running the program three times. These "short cuts" can be taken safely once the mechanics of the model are thoroughly understood

HRSTRT, HRNTVL - set for predawn analysis

CCOCRT, VISCRT - same as example 5

ACRES - same as example 5

TONS, EFPM, EFCO - not used by the program, but must have dummy inputs (values that are normally invalid are used to avoid confusion)

TFIRE - set to allow predawn analysis

THOT, TCONST, TDECAY - not used but must have dummy inputs (again invalid values are used)

LGRISE - since no plume rise is possible in this model **run,** this value is irrelevant; in this example, set to T

RFRC - not used, but need a dummy input (this example uses an invalid input)

NUMDWX through BKGCOA - same as example 5, but now have three lines of identical weather related data

NUMDRT - set to keep in synch with HRSTRT and HRNTVL

EMTQPM, EMTQCO - set low, midrange, and high estimates

EMTQH - although sensible heat emission rate might be no more **difficult** to estimate than emission rate, no plume rise is assumed; therefore, zero is used

EMTQR - set to zero, forcing zero plume rise, enabling a worst-case analysis

The **VSMOKE.IPT** file for example 6 should appear as follows:

```
66
'EXAMPLE 6 - SMOLDERING ORGANIC SOILS WITH KNOWN
EMISSIONS'
34.6 77.9 4.0 1997 8 29 3 3.0 1.0 T T T 0.02 0.0947
40.0 -1.0 -1.0 -1.0 2.5 -1.0 -1.0 -1.0 T 10.0
1997082903 72.0 1012.5 100 F 7 240. 1.0 5.0 5.0 75.0 6.0
1997082904 72.0 1012.5 100 F 7 240. 1.0 5.0 5.0 75.0 6.0
1997082905 72.0 1012.5 100 F 7 240. 1.0 5.0 5.0 75.0 6.0
1997082903 1.0E+02 4.0E+03 O.OEOO 0.0
1997082904 2.0E+02 8.0E+03 O.OEOO 0.0
1997082905 4.0E+02 1.6E+04 O.OEOO 0.0
```

Appendix III—Line-by-Line Layout of VSMOKE Output File, VSMOKE.OUT

This appendix presents a generic line-by-line description of the contents of VSMOKE.OUT and an example that shows output format for a specific test run.

Part A-Generic Line-by-Line Description

Section 1 • Echo-print

Line 1 is the header, giving program name and version number, bracketed by a series of colons, ": : : : , etc.". The version number is referenced to date of last revision and is given in yyyymmdd format.

Lines 2 and 3 are skipped.

Line 4 consists of the message,
ECHO PRINT (LIST-DIRECTED OUTPUT) **OF INPUT VALUES:**

Lines 5 to 7 are skipped.

Line 8 consists of the control variable, **NLPAGE:**

Line 9 is skipped..

Line 10 gives the value of NLPAGE as input.

Lines 11 and 12 are skipped.

Line 13 consists of the label, KTITLE:

Line 14 is skipped.

Line 15 gives the value of KTITLE, generally as it is represented in its output format. This means that apostrophe (') delimiters do not appear in KTITLE, and that single apostrophes appear where consecutive apostrophes are used within KTITLE. The methods used to process the output file may cause trailing blanks included within the input value of KTITLE to be eliminated as a part of the output file (e.g., the blanks following the colon in 'TEST CASE #1:' may be eliminated).

Lines 16 and 17 are skipped.

The following lines in this section continue the echo-print of the remaining contents of the input file. The input/output list of each line of input data is used as a header, which takes up at least one line of output. Where array variables appear, a second line is used to identify the array index value. The header line(s) are followed by a line skip, then by the values of each variable in the input/output list. The number of lines required by the list of values is dependent on the host system. The values appear in their proper order, but their format and layout are dependent upon the methodology used by the host system to process FORTRAN 77 list-directed output. Two lines are skipped to separate the list of values from the header for the next line of input data. Lines are not necessarily skipped after the last list of values for the last line of input. Page processing is not used within section 1 but is used at the end of the section. Section 2 starts with a new page.

Section 2 - Analysis for each period with significant emissions

Line 1 of each page is the header, giving program name and version number, bracketed by a series of plus signs, "+ + + + , etc." The version number is referenced to date of last revision and is given in yyyymmdd format.

Line 2 is skipped.

Line 3 gives the title (KTITLE) as input in VSMOKE.IPT. The apostrophe delimiters are not shown. At most, only the first 72 positions of line 3 are used.

Lines 4 to 12 give selected input and VSMOKE-calculated variables upon which the most critical subsequent calculations for the period depend. The output within these lines is arranged in five columns in a "VARIABLE = value" format. Line 4 appears only in the fifth column (to avoid clutter with the data on line 3). Column by column, the output includes the following:

Column 1 (lines 5 through 12):

LSTBDY - LOGICAL, set according to whether stability class is to be read from the weather data in file VSMOKE.IPT (input)
LQREAD - LOGICAL, set according to whether emissions related data are to be read from file VSMOKE.IPT (input)
LSIGHT - LOGICAL, set according to whether sightline related calculations are to be made and output (input)
LGRISE - LOGICAL, set according to whether gradual plume rise calculations are to be made and output (input)
LTOFDY - LOGICAL, set according to whether this period is in daylight (input as LTOFDY(I), if LSTBDY = TRUE)
IYEAR - INTEGER, year (input)
MO - INTEGER, month of year (input)
IDAY - INTEGER, day of month (input)

Column 2 (lines 5 through 12):

PERIOD - INTEGER, number of this period (carried as I, within the program code)
NPRIOD - INTEGER, total number of periods (input)
HRSIM - PEAL, this period's time in decimal hours
HRSTRT - REAL, start time of simulation in decimal hours (input)
HRNTVL - REAL, interval between successive periods in decimal hours (input)
ALAT - PEAL, latitude in decimal degrees, north (input)
ALONG - PEAL, longitude in decimal degrees, west (input)
TIMZON - REAL, time zone in decimal hours behind UTC (input)

Column 3 (lines 5 through 12):

IRH - INTEGER, this period's relative humidity in percent (input as IRHA(I))

IDYNT - INTEGER, set to 1 if this period is in daylight, set to 2 for darkness

ISTAB - INTEGER, this period's Turner (1964) stability class (input as ISTABA(I), if LSTBDY = TRUE)

AMIX - REAL, this period's mixing height in meters (input as AMIXA(I))

U - REAL, this period's transport windspeed in meters per second (input as UA(I))

OYINT - REAL, this period's "initial" horizontal dispersion coefficient in meters, not counting effects from non-point source modeling (input as OYINTA(I))

OZINT - REAL, this period's "initial" vertical dispersion coefficient in meters, not counting effects from the input value of RFRC and/or EMTQR(I) (input as OZINTA(I))

RHO - REAL, this period's ambient atmospheric density in kilograms per cubic meter

Column 4 (lines 5 through 12):

ELINE - REAL, effective line source length in meters

TFIRE - REAL, start time of fire in decimal hours (input)

THOT - REAL, duration of convective period of fire in decimal hours (input)

TCONST - REAL, duration of constant emissions period of fire in decimal hours (input)

TDECAY - REAL, exponential decay constant, a decay period duration parameter, in decimal hours (input)

EFPM - REAL, emission factor for particulate matter in pounds per ton of fuel consumed (input)

EFCO - REAL, emission factor for carbon monoxide in pounds per ton of fuel consumed (input)

RFRC - REAL, proportion of emissions subject to plume rise, with vertical distribution controlled by the sign of RFRC (input)

Column 5 (lines 4 to 12):

ACRES - REAL, area of emissions source in acres (input)

TONS - REAL, total mass of fuel consumed in short tons (input)

CRITPM - REAL, particulate matter concentration in micrograms per cubic meter associated with the input sightline criteria, CCOCRT and VISCRT, valid only if conditions are dry (i.e., relative humidity less than 70 percent); CRITPM is calculated if LSIGHT = TRUE, set to zero if LSIGHT = FALSE

EMTQPM(I) - REAL, this period's total emission rate for particulate matter in grams per second (input if LQREAD = TRUE)

EMTQCO(I) -REAL, this period's total emission rate for carbon monoxide in grams per second (input if LQREAD = TRUE)

EMTQH(I) -REAL, this period's total sensible heat emission rate in megawatts (input if LQREAD = TRUE)

F - REAL, this period's total buoyancy flux in meters^4 per second^3

THETA - REAL, this period's ambient potential temperature in degrees kelvin

EMTQR(I) - REAL, this period's proportion of emissions **subject** to plume rise, with vertical distribution controlled by the sign of **EMTQR(I)** (input if **LQREAD** = TRUE!)

Lines 13 and 14 are skipped.

Line 15 gives Dispersion Index **(DI)** and a descriptive adjective (see Table 4). Line 15 also displays Low Visibility Occurrence Risk Index **(LVORI)** with a brief explanation (see Table 5).

Line 16 continues the description of LVORI.

Line 17 is skipped.

Line 18 is used only if LSIGHT = TRUE, if so, line 18 is a table heading explanation, which includes the input values for critical contrast ratio (CCOCRT) and critical **crossplume** horizontal visibility (VISCRT).

Line 19 is an overall table heading, which includes the period number, simulation time, and time elapsed since the start of the fire.

Line 20 is skipped.

Lines 21 through 24 give the headings for each variable displayed in each column of the table. These variables include downwind distance in kilometers, plume height or depth in meters, horizontal and vertical dispersion coefficients in meters (including the effects of any initial dispersion), particulate matter centerline concentration including background in micrograms per cubic meter, carbon monoxide centerline concentration including background in parts per million, optional crossphnne visibility in miles (applicable if relative humidity (RH) is less than 70 percent), optional contrast ratio (for RH less than 70 percent) applicable for a **crossplume** sightline of length, VISCRT, and a repeat of downwind distance in kilometers to help in reading the table. The optional sightline parameters are calculated for a sightline constructed outward from the plume centerline in both ground-level horizontal **crossplume** directions.

Line 25 is skipped.

Lines 26 through 56 give the calculated values of the variables described in lines 21 through 24 for each downwind distance (table 6). The distances range from 0.100 to 100.000 km, using logarithmic spacing, with 10 tabular values per factor of 10 (i.e., incrementing is by a factor of $10^{0.1}$, resulting in an increase in downwind distance slightly over 25 percent per increment). The optional sightline values are accompanied by an asterisk if this period's RH equals or exceeds 70 percent.

Line 57 gives applicable values for background. Not applicable (N/A) is displayed for the plume height or depth and the horizontal and vertical dispersion coefficients. The optional sightline values are accompanied by an asterisk if the **RH** equals or exceeds 70 percent.

Line 58 is skipped.

Line 59 is used only if LSIGHT = TRUE and the RH equals or exceeds 70 percent; it consists of a warning message.

Line 60 is used only if LSIGHT = TRUE; it gives the tabular downwind distance at and beyond which the estimated ground-level horizontal crossplume sightline parameters. maintain acceptable characteristics, given an RH less than 70 percent.

Section 3 - Worst-case analysis for all periods with significant emissions

Line 1 is the header, giving program name and version number, bracketed by a series of equals signs, "= = = = , etc." The version number is referenced to date of last revision and is given in yyyymmdd format.

Line 2 is skipped.

Line 3 gives the title (KTITLE) as input in VSMOKE.IPT. The apostrophe delimiters are not shown. At most, only the first 72 positions of line 3 are used.

Line 4 is skipped.

Line 5 gives the worst (highest) RH among all periods analyzed.

Line 6 is skipped.

Line 7 gives the worst (lowest) DI among all periods analyzed and the corresponding descriptive adjective (see Table 4).

Line 8 is skipped.

Lines 9 and 10 give the worst (highest) LVORI and the corresponding brief explanation (see table 5).

Line 11 is skipped.

Line 12 gives the smoke concentration (and optional sightline) table heading.

Line 13 is used only if LSIGHT = TRUE; it gives critical contrast ratio, CCOCRT, and visibility criterion, VISCRT.

Line 14 is skipped.

Lines 15 through 18 give the headings for each variable displayed in each column of the table. These variables include downwind distance in kilometers, particulate matter concentration including background in micrograms per cubic meter, carbon monoxide concentration including background in parts per million, optional crossplume visibility in miles (applicable if RH is less than 70 percent), optional contrast ratio (for RI-I less than 70 percent) applicable for a crossplume sightline of length, VISCRT, and a repeat of downwind distance in kilometers. The optional sightline parameters are calculated for a sightline constructed outward from the plume centerline in both ground-level horizontal crossplume directions.

Line 19 is skipped.

Lines 20 through 50 give the calculated values of the variables described in lines 15 through 18 for each downwind distance. The distances range from 0.100 to

100.000 km, using logarithmic spacing, with 10 tabular values per factor of 10 (i.e, incrementing is by a factor of $10^{0.1}$, resulting in an increase in downwind distance of slightly over 25 percent per increment). The values displayed are for the worst-case (highest concentration, lowest visibility or contrast ratio) found among all analyzed periods for the specific variable at the specific downwind distance. The optional sightline values are accompanied by an asterisk if the relative humidity for any period analyzed equals or exceeds 70 percent.

Line 51 gives worst-case values for background. The optional sightline values are accompanied by an asterisk if the relative humidity for any period analyzed equals or exceeds 70 percent.

Line 52 is skipped.

Line 53 is used only if LSIGHT = TRUE and the relative humidity for any period analyzed equals or exceeds 70 percent; if so, it consists of a warning message.

Line 54 is used only if LSIGHT = TRUE; it gives the tabular downwind distance, at and beyond which the estimated ground-level horizontal crossplume sightline parameters maintain acceptable characteristics given a relative humidity less than 70 percent.

Lines 55 through 57 are skipped.

Line 58 gives a run OK flag message, which should appear as "LRUNOK = T," if no problems were diagnosed during the VSMOKE run. If problems, such as I/O processing errors, are found and system control is retained by the VSMOKE FORTRAN program, "LRUNOK = F" should appear in file VSMOKE.OUT near the end of the aborted output.

Line 59 is skipped.

Line 60 contains the end of VSMOKE run message.

In case of error with program VSMOKE-controlled termination:

A new page is generated: The header line begins with a series of open parentheses, followed by program name and version number, and ends with a series of closed parentheses. This line is followed by text that explains the nature of the error. A line is skipped followed by a run not OK message, which appears as "LRUNOK = F." A line is skipped followed by the end of VSMOKE run message. The last three lines (LRUNOK..., skipped line, and end of VSMOKE) follow the same end-of-run format as a normal run. Therefore, an automatic post-processor, diagnosing file VSMOKE.OUT, can determine whether a given run executed normally by reading to the VSMOKE.OUT end-of-file, backspacing to the LRUNOK line, and reading the value of LRUNOK.

In case of a host computer system-controlled error:

Any output from errors not anticipated by program VSMOKE logic or controllable within the confines of a FORTRAN 77 program in the host system will be dependent on the exact nature of the error and the host system characteristics, given the specific error diagnosed. The generation of a new line or a new page of output under such conditions cannot be assured. The handling of output under such conditions must be left within the purview of the user or the user's host system.

Part B-Specific Output Fiie Example

This portion of Appendix III illustrates the layout of output **file,** VSMOKE.OUT, by means of a specific example. This example is used for illustration only and should not be construed as a recommendation for input values, For this example, **VSMOKE.IPT** appears as follows:

```
60
'VSMOKE.IPT OUTPUT FILE EXAMPLE:'
33.000 82.000 5.0 1996 3 11 2 14.0 6.0 T T T 0.05 0.25
160.0 640.0 35.0 275.0 13.0 4.0 4.0 2.0 T -0.75
14 62.0 997.5 40 T 3 1500.8.0 0.0 0.0 36.0 2.75
20 41.0 998.0 90 F 6 240. 1.0 0.0 0.0 30.0 2.5
14 4.7E+01 3.7E+02 5.9E+02 -0.75
20 9.4E+00 7.4E+01 4.72E+00 +0.00
```

VSMOKE.OUT output corresponding to the input example appears on the following four pages.

```
: : : : : : : : : : : : : : : : : : : : : : : : : PROGRAM VSMOKE - VERSION 19950128 : : : : : : : : : : : : : : : : : : : : : : : : : :

                                        ECHO PRINT (LIST-DIRECTED OUTPUT) OF INFUT VALUES:

NLPAGE:

          60

KTITLE:

VSMOKE.IPT OUTPUT FILE EXAMPLE:

ALAT,ALONG,TIMZON,IYEAR,MO,IDAY,NPRICD,HRSTRT,HRNTVL,LSTBDY,LQREAD,LSIGHT,CCOCRT,VISCRT:

      33.000000       82.000000       5.000000       1996           3
          11             2      14.000000       6.000000 T T T   5.000000E-02
   2.500000E-01

ACRES,TONS,EFPM,EFCO,TFIRE,THOT,TCONST,TDECAY,LGRISE,RFRC:

     160.000000     640.000000      35.000000     275.000000
      13.000000       4.000000       4.000000       2.000000 T
   -7.500000E-01

NUMDWX(I),TTA(I),PPA(I),IRHA(I),LTOFDY(I),ISTABA(I),AMIXA(I),UA(I),OYINTA(I),OZINTA(I),BKGPMA(I),BKGCOA(I);
                                        FOR I = 1:

          14      62.000000     997.500000          40 T           3
    1500.000000       8.000000   0.000000E+00   0.000000E+00
      36.000000       2.750000

NUMDWX(I),TTA(I),PPA(I),IRHA(I),LTOFDY(I),ISTABA(I),AMIXA(I),UA(I),OYINTA(I),OZINTA(I),BKGPMA(I),BKGCOA(I);
                                        FOR I = 2:

          20      41.000000     998.000000          90 F           6
     240.000000       1.000000   0.000000E+00   O.DDDDDDE+DD
      30.000000       2.500000

NUMDRT(I),EMTQPM(I),EMTQCO(I),EMTQH(I),EMTQR(I);
                      FOR I = 1:

          14      47.000000     370.000000     590.000000   -7.500000E-01

NUMDRT(I),EMTQPM(I),EMTQCO(I),EMTQH(I),EMTQR(I);
                      FOR I = 2:

          20       9.400000      74.000000       4.720000    0.000000E+00
```

+ **PROGRAM VSMOKE - VERSION 19950128** +

VSMOKE.IPT OUTPUT FILE **EXAMPLE:**

				ACRES = 160.000
LSTBDY = T	PERIOD = 1	IRH = 40	ELINE = 804.6720	TONS = 6bo.m
LQREAD = T	NPRIOD = 2	IDYNT = 1	TFIRE = 13.0000	CRITPM = 2233.754
LSIGHT = T	NRSIN = 14.0000	ISTAB = 3	THOT = 4.0000	EMTQPM(I) = .4700000E+02
LGRISE = T	HRSTRT = 14.0000	AMIX = 1500.	TCONST = 4.0000	EMTQCO(I) = .3700000E+03
LTOFDY = T	NRNTVL = 6.0000	U = 8.0	TDECAY = 2.0000	EMTQH(I) = .5900000E+03
IYEAR = 1996	ALAT = 33.000	OYINT = .000	EFPN = 35.0000	F = .5193239E+04
MO = 3	ALONG = 82.000	OZINT 3 .000	EFCO = 275.0000	THETA = .2900240E+03
IDAY = 11	TIMZON = 5.000	RHO = 1.195559	RFRC = -.7500	EMTQR(I) = -.7500000E+00

DISPERSION INDEX = 74 - **GOOD**

LOU VISIBILITY OCCURRENCE RISK INDEX = 1 - (EQUALS BASE LINE)
(THE BASE LINE RISK OF LOU VISIBILITY OCCURRENCE **IS** ABOUT 1 IN **1000)**

THE **FOLLOWING** TABLE IS BASED ON A CRITICAL **CONTRAST** RATIO = 0.050000, **WITH HORIZONTAL** CROSSPLLME VISIBILITY = **.2500** MILES.
PERIOD 1 - **SMOKE** CONCENTRATION/VISIBILITY TABLE: NRSIN = 14.0000 - - - **THAT** IS, **1.0000 HOURS** AFTER FIRE START **TIME.**

DOWNWIND DISTANCE FRON FIRE (KM)	PLUME HEIGHT/ DEPTH (METERS)	HORIZONTAL DISPERSION COEFFICIENT (METERS)	VERTICAL DISPERSION COEFFICIENT (METERS)	PM CENTERLINE CONCENTRATION (INCL. BKGPM) (UG/M**3)	CO CENTERLINE CONCENTRATION (INCL. BKGCO) (PPM)	CROSSPLUME VISIBILITY FOR LOW RH (MILES)	CONTRAST RATIO AT .2500 WILES	DOWNWIND DISTANCE FROM FIRE (KM)
.100	74.618	12.463	7.442	305.083	4.521819	10.46659	.660216	.100
.126	86.998	15.416	9.186	257.476	4.208341	11.05434	.703744	.126
.158	101.432	19.064	11.340	218.412	3.951121	11.53660	.741595	.158
.200	118.261	23.569	13.998	186.341	3.739941	11.93255	.774188	.200
.251	137.883	29.129	17.280	159.994	3.566458	12.25781	.802032	.251
.316	160.759	35.991	21.331	138.337	3.423855	12.52518	.825669	.316
.398	187.432	44.454	26.331	120.524	3.306562	12.74510	.845631	.398
.501	218.529	54.890	32.504	105.863	3.210025	12.92610	.862423	.501
.631	254.786	67.752	40.124	93.789	3.130517	13.07517	.876511	.631
.794	297.059	83.599	49.530	83.837	3.064991	13.19802	.888341	.794
1.000	346.345	103.114	61.141	75.626	3.010925	13.29935	.898347	1.000
1.259	403.809	127.135	75.474	68.806	2.966014	13.38297	.906917	1.259
1.585	470.807	156.688	93.167	62.983	2.927676	13.45203	.914356	1.585
1.995	548.921	193.031	115.008	57.798	2.893533	13.50911	.920866	1.995
2.512	639.994	237.698	141.969	53.111	2.862671	13.55633	.926543	2.512
3.162	746.179	292.567	175.250	49.003	2.835619	13.59541	.931398	3.162
3.981	820.344	359.928	216.333	45.872	2.815001	13.62309	.935087	3.981
5.012	820.344	442.576	267.047	43.713	2.800788	13.63903	.937636	5.012
6.310	820.344	543.915	329.650	41.950	2.789177	13.65270	.939747	6.310
7.943	820.344	668.088	406.928	40.512	2.779712	13.66561	.941491	-7.943
10.000	820.344	820.132	502.322	39.345	2.772027	13.67884	.942934	10.000
12.589	820.344	low.162	620.080	38.419	2.765926	13.69251	.944082	12.589
15.849	820.344	1233.594	765.442	37.709	2.761255	13.70607	.944974	15.849
19.953	820.344	1511.408	944.882	37.189	2.757830	13.71867	.945628	19.953
25.119	820.344	1850.459	1166.386	36.859	2.755656	13.72698	.946044	25.119
31.623	820.344	2263.851	1439.818	36.690	2.754545	13.72819	.946257	31.623
39.811	820.344	2767.369	1777.349	36.563	2.753707	13.72848	.946419	39.811
50.119	820.344	3379.9%	2194.005	36.461	2.753037	13.72857	.946548	50.119
63.0%	820.344	4124.507	2708.336	36.378	2.752491	13.72896	.946653	63.096
79.433	820.344	5028.163	3343.240	36.310	2.752044	13.73020	.946739	79.433
100.000	820.344	6123.506	4126.982	36.255	2.751679	13.73279	.946810	100.000
BACKGROUND	N/A	N/A	N/A	36.000	2.750000	13.78861	.947133	BACKGROUND

DRY **WEATHER** CROSSPLLME **VISIBILITIES** ARE AT LEAST **.2500** MILES, AT AND **BEYOND** **.100 KM** FROM THE FIRE.

+ **PROGRAM VSMOKE - VERSION 19950128** •

VSMOKE.IPT OUTPUT FILE **EXAMPLE:**

				ACRES = 160.000
LSTBDY = T	PERIOD = 2	IRH = 90	ELINE = 804.6720	TONS = 640.000
LQREAD = T	NPRIOD = 2	IDYNT = 2	TFIRE = 13.0000	CRITPM = 2233.7%
LSIGHT = T	HRSIM = 20.0000	ISTAB = 6	THOT = 4.0000	EMTQPM(I) = .9400000E+01
LGRISE = T	HRBTRT = 1 4 . m	AMIX = 240.	TCONST = 4.0000	EMTQCO(I) = .7400000E+02
LTOFDY = F	HRNTVL = 6.0000	u = 1.0	TDECAY = 2.0000	EMTQH(I) = .4720000E+01
IYEAR = 1996	ALAT = 33.000	OYINT = .000	EFPM = 35.0000	F = .4154591E+02
Ho = 3	ALONG = 82.000	OZINT = .OOO	EFCD = 275.0000	THETA = .2783091E+03
IDAY = 11	TIMZON = 5.000	RHD = 1.246205	RFRC = -.7500	EMTQR(I) = .0000000E+00

DISPERSION INDEX = 1 • VERY **POOR**

LOW VISIBILITY **OCCURRENCE** RISK INDEX = 7 • (20 TO 40 TIRES BABE LINE)
(THE BASE LINE RISK OF LOU VISIBILITY **OCCURRENCE** IS **ABOUT** 1 IN **1000)**

THE **FOLLOWING TABLE** IS **BASED ON** A CRITICAL **CONTRAST** RATIO = **0.050000,** WITH **HORIZONTAL CROSSPLUME** VISIBILITY = **.2500** RILES.
PERIDD 2 • **SMOKE CONCENTRATION/VISIBILITY** TABLE: **HRSIM** = 20.0000 • • • THAT **IS, 7.0000** HOURS AFTER FIRE START TIRE.

DOWNWIND DISTANCE FRDR FIRE (KM)	PLUME HEIGHT/ DRPTH METERS)	HORIZONTAL DISPERSION COEFFICIENT (METERS)	VERTICAL DISPERSION COEFFICIENT (METERS)	PM CENTERLINE CONCENTRATION (INCL. BKGPM) (UG/M**3)	CD CENTERLINE CONCENTRATION (INCL. BKGCO) (PPM)	CROSSPLUME VISIBILITY FOR LOW RH (MILES)	CONTRAST RATIO AT .2500 MILES	DOWNWIND DISTANCE FROM FIRE (KM)
.100	77.512	4.069	2.326	4038.006	27.818780	.13814 *	.004421 *	.100
.126	77.512	5.037	2.806	3351.777	23.483840	.16639 *	.011096 •	.126
.158	77.512	6.233	3.386	2783.040	19.891090	.20033 *	.023792 *	.158
.200	77.512	7.711	4.085	2311.678	16.913480	.24110 •	.044767 *	.200
.251	n.512	9.537	4.894	1934.640	14.531710	.28798 •	.074228 •	.251
.316	77.512	11.791	5.862	1620.032	12.544310	.34375 ☒	.113189 *	.316
.398	77.512	14.573	7.022	1357.391	10.885200	.41005 *	.160983 *	.398
.501	77.512	18.005	8.411	1130.133	9.500134	.49531 *	.216015 *	.501
.631	77.512	22.238	10.075	955.092	8.343853	2.77950'	.276118 •	.631
.794	77.512	27.455	11.918	812.072	7.440386	4.85225 •	.334499 *	.794
1.000	77.512	33.884	13.953	698.008	6.719839	6.50535 •	.389790 *	1.000
1.259	77.512	41.802	16.140	607.503	6.148119	7.81701 *	.440093 *	1.259
1.585	77.512	51.548	lb.669	529.261	5.653856	8.95096 •	.488784 *	1.585
1.995	77.512	63.538	21.5%	461.619	5.226559	9.93128 •	.535217 •	1.995
2.512	T1.512	78.283	24.488	410.628	4.904448	10.67027 •	.573261 *	2.512
3.162	77.512	96.404	27.645	367.147	4.629776	11.30029 *	.608364 *	3.162
3.981	77.512	118.661	30.769	332.719	4.412292	11.79633 *	.638837 *	3.981
5.012	77.512	145.981	34.245	300.586	4.209303	12.24201 *	.669593 •	5.012
6.310	77.512	179.495	38.114	268.435	4.006206	12.64243 •	.701192 •	6.310
7.943	77.512	220.578	42.156	236.032	3.801514	12.98222 •	.732599 *	7.943
10.000	77.512	270.902	46.384	203.317	3.594852	13.27425 •	.764048 •	10.000
12.589	77.512	332.501	51.036	171.308	3.392647	13.53967 *	.795269 *	12.589
15.849	77.512	407.839	55.880	142.774	3.212402	13.76912 •	.824260 *	15.849
19.953	77.512	499.901	60.248	119.588	3.065932	13.94434 •	.848809 *	19.953
25.119	77.512	612.298	64.956	100.150	2.943142	14.10686 •	.870327 *	25.119
31.623	77.512	749.308	69.838	84.540	2.844529	14.25223 *	.888150 •	31.623
39.811	77.512	916.425	74.392	72.519	2.768593	14.37065 *	.902242 *	39.811
50.119	77.512	1119.725	79.244	63.009	2.708522	14.48181 *	.913632 •	50.119
63.0%	77.512	1366.872	84.170	55.637	2.661947	14.58158 •	.922627 *	63.0%
79.433	77.512	1666.943	M.485	50.090	2.626911	14.65986 •	.929451 *	79.433
100.000	77.512	2030.775	93.022	45.736	2.599406	14.73432 *	.934847 *	100.000
BACKGROUND	N/A	N/A	N/A	30.000	2.500000	16.18662 *	.954785 •	BACKGROUND

• • RELATIVE **HUMIDITY EQUALS OR** EXCEEDS 70 PER CENT, ACTUAL **VISIBILITIES** AND **CONTRASTS MAY** BE MUCH LESS **THAN** ESTIMATED.

* DRY **WEATHER CROSSPLUME VISIBILITIES** ARE AT LEAST **.2500** MILES, AT AND **BEYOND .251 KM FROM** THE FIRE.

* PROGRAM VSMOKE - VERSION 19950128 *

VSMOKE.IPT OUTPUT FILE EXAMPLE:

WORST (HIGHEST) RELATIVE HUMIDITY = 90 PER CENT

WORST (LOWEST) DISPERSION INDEX = 1 • VERY PWR

WORST (HIGHEST) LOW VISIBILITY OCCURRENCE RISK INDEX = 7 • (20 TO 40 TIMES BASE LINE)
(THE BASE LINE RISK OF LOW VISIBILITY OCCURRENCE IS ABOUT 1 IN 1000)

WORST INDIVIDUAL OCCURRENCE SMOKE CONCENTRATION/VISIBILITY TABLE:
THE FOLLOWING TABLE IS BASED ON A CRITICAL CONTRAST RATIO = 0.050000, WITH HORIZONTAL CROSSPLUME VISIBILITY = .2500 RILES.

DOWNWIND DISTANCE FROM FIRE (KM)	PN CENTERLINE CONCENTRATION (INCL. BKGPM) (UG/M**3)	CO CENTERLINE CONCENTRATION (INCL. BKGCO) (PPM)	CROSSPLUME VISIBILITY FOR LOW RH (MILES)	CONTRAST RATIO AT .2500 RILES	DOWNWIND DISTANCE FROM FIRE (KM)
.100	4038.006	27.818780	.13814 *	.004421 •	.100
.126	3351.777	23.483840	.16639 *	.011096 *	.126
.158	2783.040	19.891090	.20033 •	.023792 *	.158
.200	2311.678	16.9134%	.24110 *	.044767 •	.200
.251	1934.640	14.531710	.28798 •	.074228 •	.251
.316	1620.052	12.544310	.34375 •	.113189 *	.316
.398	1357.391	10.885200	.41005 *	.160983 *	.398
.501	1138.133	9.500134	.49531 •	.216015 •	.501
.631	955.092	8.343853	2.77950 *	.276118 *	.631
.794	812.072	7.440386	4.85225 •	.334499 •	.794
1.000	698.008	6.719839	6.50535 •	.389790 *	1.000
1.259	607.503	6.148119	7.81791 *	.440093 •	1.259
1.585	529.261	5.653856	8.95096 *	.488784 •	1.585
1.995	461.619	5.226559	9.93128 *	.535217 *	1.995
2.512	410.628	4.904448	10.67027 •	.573261 *	2.512
3.162	367.147	4.629776	11.30029 •	.608364 *	3.162
3.981	332.719	4.412292	-11.79633 *	.638837 *	3.981
5.012	300.586	4.299303	12.24201 •	.669593 •	5.012
6.310	260.435	4.0062%	12.64243 *	.701192 *	6.310
7.943	236.032	3.801514	12.98222 •	.732599 *	7.943
10.000	203.317	3.594652	13.27425 *	.764048 *	10.000
12.589	171.303	3.392647	13.53967 •	.795269 •	12.589
15.849	142.774	3.212402	13.70607 •	.824260 •	15.849
19.953	119.508	3.965932	13.71867 •	.848809 *	19.953
25.119	100.150	2.913142	13.72698 •	.870327 *	25.119
31.623	84.540	2.844529	13.72819 *	.888150 •	31.623
39.811	72.519	2.768593	13.72818 •	.902242 *	39.811
50.119	63.009	2.753037	13.72857 •	.913632 •	50.119
63.096	55.637	2.752491	13.728% *	.922627 *	63.096
79.433	50.090	2.752044	13.73020 *	.929451 *	79.433
100.000	45.736	2.751679	13.73279 *	.934847 *	100.000
SACKGRDUND	36.000	2.750000	13.78861 •	.947133 *	BACKGROUND

• RELATIVE HUMIDITY EQUALS OR EXCEEDS 70 PER CENT, ACTUAL VISIBILITIES AND CONTRASTS RAY SE MUCH LESS THAN ESTIMATED.
* DRY WEATHER CROSSPLUME VISIBILITIES ARE AT LEAST .2500 RILES, AT AND BEYOND .251 KM FROM THE FIRE.

LRUNOK = T

END OF VSMOKE RUN.

Appendix IV—Index of Output Data

This appendix gives a detailed index of line and column position and format for VSMOKE output variables and supporting textual information as it appears in the final output file, VSMOKE.OUT. Included in the appendix are line number, column position(s), and (as applicable) input/output format. This appendix is intended to aid those developing automated post-processors. The data in the appendix are given by section and line number, following the order given in Appendix III. Even though text is delimited by quotation marks (") in this appendix, quotes do not appear in the output. Variable names are in capital letters, and brief explanations follow in parentheses if needed. Explanations are separated from the variable name by two or more blanks. The format information follows FORTRAN 77 conventions:

1. A - denotes input/output processing of CHARACTER data.

2. **nnX** - denotes one or more (as specified by nn) position "skips" (generally, used only for blanks).

3. Lnn - denotes LOGICAL data, where nn is the number of spaces allowed for the data; generally, only the rightmost position is used to display T or F as appropriate.

4. Inn - denotes INTEGER data, where nn is the number of spaces allowed for the data.

5. **Fnn.dd** - denotes REAL data displayed in decimal notation, where nn is the total number of spaces allowed for the data; space for the decimal point and possible sign must be included, dd is number of places displayed to the right of the decimal point.

6. **Enn.dd** - denotes REAL data displayed in exponential notation, where M is the total number of spaces allowed for the data, and dd is the number of places **displayed** to the right of the decimal point within the mantissa; M must be at least seven spaces larger than dd to allow space for the decimal point and sign in the mantissa and space for the display of the exponent; exponent display is generally of the form Espp, where s is the sign and pp is the positive or negative power of 10.

Should VSMOKE generate a numerical value that "overflows" the space allowed, asterisks will occupy the complete field. An attempt has been made to design VSMOKE so this problem will not occur under **ordinary** operations using physically realistic input variables. However, such behavior can be "forced" for certain output fields when the code is mathematically exercised. The user should note that asterisks cannot be successfully read by a FORTRAN 77 program directly into a numerical data field. Because VSMOKE outputs asterisks within its table headings and uses them to display high humidity warnings for **sightline-**related variables, any FORTRAN 77 post-processor making specific use of numerical data will need to test for asterisks within the various specific positions allocated to numerical data within the output file.

Section 1 - Echo-Print

Variable/Text	Line(s)	Column(s)	Format
Leading colons	1	odd, 1- 45	A
Blank spaces for colons	1	even, 2- 46	A
Blank leader within KHEADR	1	47	A
"PROGRAM VSMOKE", within KHEADR	1	48- 61	A
" - ", within KHEADR	1	62- 64	A
"VERSION ", within KHEADR	1	65- 72	A
yyyymmdd, within KHEADR	1	73- 80	A[1]
Blank trailer within KHEADR	1	81	A
Blank spaces for colons	1	even, 82- 126	A
Trailing colons	1	odd, 83-127	A
...	Lines 2 and 3 are skipped.		
Blanks	4	1- 30	30X
Text for section header	4	31- 80	A
...	Lines 5-7 are skipped.		
Text - "KTITLE:"	8	1- 7	A
...	Line 9 is skipped.		
KTITLE (echo-print)	10	1- 72	A

. ..The remainder of Section 1 consists of an echo-print of the data within the input file, **VSMOKE.IPT.** The length of the remainder of Section 1 and the appearance and location of **echo**-print data within the output **file, VSMOKE.OUT,** depend upon both the data within the input file and the methods used by the host computer system to process FORTRAN 77 list-directed output statements.

[1] 3I2 may be used.

Variable/Text	Line(s)	Column(s)	Format
Leading plus signs	1	odd, 1- 45	A
Blank spacers for plus signs	1	even, 2- 46	A
Blank leader within KHEADR	1	47	A
“PROGRAM VSMOKE", within KHEADR	1	48- 61	A
" - ", within KHEADR	1	62- 64	A
“VERSION”, within KHEADR	1	65- 72	A
yymmdd, with KHEADR	1	73- 80	A[1]
Blank trailer within KHEADR	1	81	A
Blank spacers for plus signs	1	even, 82-126	A
Trailing plus signs	1	odd, 83-127	A
Line 2 is skipped.			
KTITLE	3	1- 72	A
Blanks	4	1-102	102x
"ACRES ="	4	103-113	A
ACRES	4	114-127	F14.3
"LSTBDY ="	5	1- 8	A
LSTBDY (T/F value is on col. 13)	5	9- 13	L5
Blanks	5	14- 21	8X
"PERIOD ="	5	22- 29	A
I (that is, the PERIOD)	5	30- 34	I5
Blanks	5	35- 47	13x
"IRH ="	5	48- 55	A
IRH	5	56- 60	I5
Blanks	5	61- 74	14x
"ELINE ="	5	75- 82	A
ELINE	5	83- 93	F11.4
Blanks	5	94- 102	9x
"TONS ="	5	103- 113	A
TONS	5	114- 127	F14.3
"LQREAD ="	6	1- 8	A
LQREAD (T/F value is on col. 13)	6	9- 13	L5
Blanks	6	14- 21	8X
"NPRIOD ="	6	22- 29	A
NPRIOD	6	30- 34	I5
Blanks	6	35- 47	13x
"IDYNT ="	6	48- 55	A
IDYNT	6	56- 60	I5

[1] 3I2 may be used.

Continued

Section 2 - Period-by-Period Analysis (Continued)

Variable/Text	Line(s)	Column(s)	Format
Blanks	6	61- 74	14x
"TFIRE ="	6	75- 82	A
TFIRE	6	83- 93	F11.4
Blanks	6	94-102	9x
"CRITPM ="	6	103-113	A
CRITPM	6	114-127	F14.3
"LSIGHT ="	7	1- 8	A
LSIGHT (T/F value is on col. 13)	7	9- 13	L5
Blanks	7	14- 21	8X
"HRSIM ="	7	22- 29	A
HRSIM	7	30- 39	F10.4
Blanks	7	40- 47	8X
"ISTAB ="	7	48- 55	A
ISTAB	7	56- 60	I5
Blanks	7	61- 74	14x
"THOT ="	7	75- 82	A
THOT	7	83- 93	F11.4
Blanks	7	94-102	9x
"EMTQPM(I) ="	7	103-113	A
EMTQPM(I)	7	114-127	E14.7
"LGRISE ="	8	1- 8	A
LGRISE (T/F value is on col. 13)	8	9- 13	L5
Blanks	8	14- 21	8X
"HRSTRT ="	8	22- 29	A
HRSTRT	8	30- 39	F10.4
Blanks	8	40- 47	8X
"AMIX ="	8	48- 55	A
AMIX	8	56- 61	F6.0
Blanks	8	62- 74	13x
"TCONST ="	8	75- 82	A
TCONST	8	83- 93	F11.4
Blanks	8	94-102	9x
"EMTQCO(I) ="	8	103-113	A
EMTQCO(I)	8	114-127	E14.7
"LTOFDY ="	9	1- 8	A
LTOFDY (T/F value is on col. 13)	9	9- 13	L5
Blanks	9	14- 21	8X
"HRNTVL ="	9	22- 29	A
HRNTVL	9	30- 39	F10.4
Blanks	9	40- 47	8X
"U ="	9	48- 55	A
U	9	56- 62	F7.1

Section 2 - Period-by-Period Analysis (Continued)

Variable/Text	Line(s)	Column(s)	Format
Blanks	9	63- 74	12x
"TDECAY ="	9	75- 82	A
TDECAY	9	83- 93	F11.4
Blanks	9	94-102	9x
"EMTQH(I) ="	9	103-l 13	A
EMTQH(I)	9	114-127	E14.7
"IYEAR ="	10	1- 8	A
IYEAR	10	9- 13	I5
Blanks	10	14- 21	8X
"ALAT ="	10	22- 29	A
ALAT	10	30- 39	F10.4
Blanks	10	40- 47	8X
"OYINT ="	10	48- 55	A
OYINT	10	56- 64	F9.3
Blanks	10	65- 74	10x
"EFPM ="	10	75- 82	A
EFPM	10	83- 93	F11.4
Blanks	10	94-102	9x
"F ="	10	103-l 13	A
F	10	114-127	E14.7
"MO ="	11	1- 8	A
MO	11	9- 13	I5
Blanks	11	14- 21	8X
"ALONG ="	11	22- 29	A
ALONG	11	30- 39	F10.4
Blanks	11	40- 47	8X
"OZINT ="	11	48- 55	A
OZINT	11	56- 64	F9.3
Blanks	11	65- 74	10x
"EFCO ="	11	75- 82	A
EFCO	11	83- 93	F11.4
Blanks	11	94-102	9x
"THETA ="	11	103-l 13	A
THETA	11	114-127	E14.7
"IDAY ="	12	1- 8	A
IDAY	12	9- 13	I5
Blanks	12	14- 21	8X
"TIMZON ="	12	22- 29	A
TIMZON	12	30- 39	F10.4
Blanks	12	40- 47	8X
"RHO ="	12	48- 55	A
RHO	12	56- 67	F12.6

Variable/Text	Line(s)	Column(s)	Format
Blanks	12	68- 74	7x
"RFRC ="	12	75- 82	A
RFRC	12	83- 93	F11.4
Blanks	12	94-102	9x
"EMTQR(I) ="	12	103-113	A
EMTQR(I)	12	114-127	E14.7
	Line 13 is skipped.		
	Line 14 is skipped.		
"DISPERSION INDEX ="	15	1- 18	A
IDSPNX (rounded DI value)	15	19- 22	I4
" "	15	23- 25	A
KDSPNX(IDX) (DI adjective)	15	26- 37	A
Blanks	15	38- 55	18X
"LOW VISIBILITY OCCURRENCE"	15	56- 80	A
" RISK INDEX ="	15	81- 93	A
ILVRI (value of LVORI)	15	94- 96	I3
" "	15	97- 99	A
KLVORI(ILVRI) (describes LVORI)	15	100-127	A
Blanks	16	1- 54	54x
"(THE BASE LINE RISK OF LOW"	16	55- 80	A
" VISIBILITY OCCURRENCE IS "	16	81-106	A
"ABOUT 1 IN 1000)"	16	107-122	A
	Line 17 is skipped.		

IF LSIGHT = TRUE, THEN:

Line 18 appears as follows:

Variable/Text	Line(s)	Column(s)	Format
"THE FOLLOWING TABLE IS BASED ON"	18	1- 31	A
" A CRITICAL CONTRAST RATIO = 0"	18	32- 61	A[2]
CCOCRT	18	62- 68	F7.6
", WITH HORIZONTAL CROSSPLUME"	18	69- 97	A
" VISIBILITY = "	18	98-110	A
VISCRT	18	111-120	F10.4
" MILES."	18	121-127	A

ELSE IF LSIGHT = FALSE, THEN:

Line 18 is skipped.

END Line 18 block IF.

[2] **Can use F8.6 for cd. 61-68**

Section 2 - Period-by-Period Analysis (Continued)

Variable/Text	Line(s)	Column(s)	Format
"PERIOD"	19	1- 6	A
I (that is, the PERIOD)	19	7- 10	14
" -SMOKECONCENTRATION"	19	11- 34	A
	Line 19 (continued)		
IF LSIGHT = TRUE, THEN:			
	Line 19, Col. 35- 54 appears as follows:		
"/VISIBILITY TABLE: "	19	35- 54	A
ELSE IF LSIGHT = FALSE, THEN:			
	Line 19, Col. 35- 54 appears as follows:		
" TABLE: ----- "	19	35- 54	A
END Line 19, Col. 35-127 block IF			
"HRSIM ="	19	55- 61	A
HRSIM	19	62- 71	F10.4
" --- THAT IS,"	19	72- 88	A
HRFIRE	19	89- 98	F10.4
" HOURS AFTER FIRE START TIME."	19	99-127	A
	Line 20 is skipped.		
IF LSIGHT = TRUE, THEN:			
	Lines 21-24 appear as follows:		
"DOWNWIND "	21	1- 13	A
" PLUME "	21	14- 25	A
"HORIZONTAL "	21	26- 39	A
" VERTICAL "	21	40- 54	A
"PMCENTERLINE "	21	55- 72	A
"CO CENTERLIIW "	21	73- 89	A
"CROSSPLUME "	21	90-103	A
" CONTRAST"	21	104-l 13	A
" DOWNWIND"	21	114-125	A
"DISTANCE "	22	1- 13	A
"HEIGHT/ "	22	14- 25	A
"DISPERSION "	22	26- 39	A
"DISPERSION "	22	40- 54	A
"CONCENTRATION "	22	55- 72	A

Variable/Text	Line(s)	Column(s)	Format
"CONCENTRATION "	22	73- 89	A
"VISIBILITY "	22	90-103	A
" RATIO AT"	22	104-113	A
" DISTANCE"	22	114-125	A
"FROM FIRE "	23	1- 13	A
" DEPTH "	23	14- 25	A
"COEFFICIENT "	23	26- 39	A
"COEFFICIENT "	23	40- 54	A
"(INCL. BKGPM) "	23	55- 72	A
"(INCL. BKGCO) "	23	73- 89	A
"FOR LOW RI-I "	23	90-103	A
VISCRT	23	104-113	F10.4
" FROMFIRE"	23	114-126	A
" (KM) "	24	1- 13	A
"(METERS) "	24	14- 25	A
" (METERS) "	24	26- 39	A
" (METERS) "	24	40- 54	A
" (UG M^{-3}) "	24	55- 72	A
" (PPM) "	24	73- 89	A
" (MILES) "	24	90-103	A
" MILES "	24	104-113	A
" (KM)"	24	114-123	A

ELSE IF LSIGHT = FALSE, THEN

Lines 21-24 appear as follows:

Variable/Text	Line(s)	Column(s)	Format
"DOWNWIND "	21	1- 13	A
" PLUME "	21	14- 25	A
"HORIZONTAL "	21	26- 39	A
" VERTICAL "	21	40- 54	A
"PM CENTERLINE "	21	55- 72	A
"CO CENTERLINE"	21	73- 85	A
" DOWNWIND"	21	86- 97	A
"DISTANCE "	22	1- 13	A
" HEIGHT/ "	22	14- 25	A
"DISPERSION "	22	26- 39	A
"DISPERSION "	22	40- 54	A
"CONCENTRATION "	22	55- 72	A
"CONCENTRATION"	22	73- 85	A
" DISTANCE"	22	86- 97	A
"FROM FIRE "	23	1- 13	A
" DEPTH "	23	14- 25	A

Variable/Text	Line(s)	Column(s)	Format
"COEFFICIENT "	23	26- 39	A
"COEFFICIENT "	23	40- 54	A
"(INCL. BKGPM) "	23	55- 72	A
"(INCL. BKGCO)"	23	73- 85	A
" FROM FIRE"	23	86- 98	A
" (KM) "	24	1- 13	A
"(METERS) "	24	14- 25	A
" (METERS) "	24	26- 39	A
" (METERS) "	24	40- 54	A
" (UG M^{-3}) "	24	55- 72	A
" (PPM) "	24	73- 85	A
" (KM)"	24	86- 95	A

END Lines 21 to24 **block IF.**

Line 25 is skipped.

IF LSIGHT = TRUE, THEN:

Lines 26-56 appear as follows:

XKM (downwind distance)	26-56	1- 8	F8.3
H (plume height/depth)	26-56	9- 21	F13.3
OY (sigma-y)	26-56	22- 35	F14.3
OZ (sigma-z)	26-56	36- 49	F14.3
CHIPM (particulate conc.)	26-56	50- 67	F18.3
CHICO (carbon monoxide conc.)	26-56	68- 85	F18.6
VXPLMI (sightline visibility)	26-56	86- 99	F14.5
Blank	26-56	100	1x
Blank (or asterisk, IF RH GE.70%)	26-56	101	A
CCOVCT (contrast ratio)	26-56	102-113	F12.6
Blank	26-56	114	1x
Blank (or asterisk, IF RH.GE.70%)	26-56	115	A
Blanks	26-56	116-117	2x
XKM (repeated for readability)	26-56	118-125	F8.3

ELSE IF LSIGHT = FALSE, THEN

Lines 26-56 appear as follows:

XKM (downwind distance)	26-56	1- 8	F8.3
H (plume height/depth)	26-56	9- 21	F13.3
OY (sigma-y)	26-56	22- 35	F14.3
OZ (sigma-z)	26-56	36- 49	F14.3
CHIPM (particulate conc.)	26-56	50- 67	F18.3

Variable/Text	Line(s)	Column(s)	Format
CHICO (carbon monoxide conc.)	26-56	68- 85	F18.6
Blanks	26-56	86- 89	4x
XKM (repeated for readability)	26-56	90- 97	F8.3

END Lines 26 to 56 block **IF**.

IF LSIGHT = TRUE, **THEN:**

Line 57 appears as follows:

Variable/Text	Line(s)	Column(s)	Format
"BACKGROUND"	57	1- 10	A
Blanks	57	11- 16	A
"N/A"	57	17- 19	A
Blanks	57	20- 30	A
"N/A"	57	31- 33	A
Blanks	57	34- 44	A
"N/A"	57	45- 47	A
Blanks	57	48- 51	A
CHIPM (particulate conc.)	57	52- 67	F16.3
CHICO (carbon monoxide conc.)	57	68- 85	F18.6
VXPLMI (sightline visibility)	57	86- 99	F14.5
Blank	57	loo	1x
Blank (or asterisk, IF RH.GE.70%)	57	101	4
CCOVCT (contrast ratio)	57	102-l 13	F12.6
Blank	57	114	1x
Blank (or asterisk, IF RH.GE 70%)	57	115	A
Blanks	57	116-117	2x
"BACKGROUND" (repeated)	57	118-127	A

ELSE IF LSIGHT = FALSE, THEN

Line 57 appears as follows:

Variable/Text	Line(s)	Column(s)	Format
"BACKGROUND"	57	1- 10	A
Blanks	57	11- 16	A
"N/A"	57	17- 19	A
Blanks	57	20- 30	A
"N/A"	57	31- 33	A
Blanks	57	34- 44	A
"N/A"	57	45- 47	A
Blanks	57	48- 51	A
CHIPM (particulate concentration)	57	52- 67	F16.3
CHICO (carbon monoxide concentration)	57	68- 85	F18.6
Blanks	57	86- 89	4x

Section 2 - Period-by-Period Analysis (Continued)

Variable/Text	Line(s)	Column(s)	Format
"BACKGROUND" (repeated)	57	90- 99	A

END Line 57 block **IF**.

Line 58 is skipped.

IF LSIGHT = TRUE, **AND** RELATIVE HUMIDITY EQUALS OR EXCEEDS 70 PERCENT, THEN:

Line 59 appears as follows:

"* RELATIVE HUMIDITY "	59	1- 24	A
"EQUALS OR EXCEEDS 70 PERCENT,"	59	25- 54	A
" ACTUAL VISIBILITIES AND "	59	55- 79	A
"CONTRAST RATIOS MAY BE MUCH "	59	80-101	A
"LESS THAN ESTIMATED."	59	102-121	A

ELSE IF LSIGHT = FALSE, Q&RELATIVE HUMIDITY IS LESS THAN 70 PERCENT, THEN:

Line 59 is skipped.

END Line 59 block **IF**.

IF LSIGHT = TRUE, THEN:

Line 60 appears as follows:

Blank (or asterisk **IF RH.GE.70%)**	60	1	A
Blanks	60	2- 10	A
"DRY WEATHER CROSSPLUME "	60	11- 33	A
"**VISIBILITIES** ARE "	60	34- 50	A
"AT LEAST", **OR** "LESS THAN "[3]	60	51- 60	A
VISCRT	60	61- 70	F10.4
" MILES, AT AND BEYOND "	60	71- 92	
DSKM(JVSOK), **OR** "100.000"	60	93- 99	**F7.3**[5]
" KM FROM THE FIRE."	60	100-l 17	A

LSE IF LSIGHT = FALSE, THEN

Line 60 is skipped.

END Line 60 block **IF**.

---

[3] Lii **60:** First **alternative** applies if the crossplume visibility 100.000 **km** downwind is at least VISCRT.

[4] Line 60: **DSKM(JVSOK)** is the shortest downwind distance for which **estimated** visibility is at least VISCRT at this and all longer distances in the program.

[5] **OK for both**

Variable/Text	Line(s)	Column(s)	Format
Leading equals signs	1	odd, 1- 45	A
Blank spacers for equals signs	1	even, 2- 46	A
Blank leader within KHEADR	1	47	A
"PROGRAM VSMOKE", within KHEADR	1	48- 61	A
" - ", within KHEADR	1	62- 64	A
"VERSION ", within KHEADR	1	65- 72	A
yymmdd, withiu KHEADR	1	73- 80	A'
Blank trailer within KHEADR	1	81	A
Blank spacers for equals signs	1	even, 82- 126	A
Trailing equals signs	1	odd, 83- 127	A
	Line 2 is skipped.		
KTITLE	3	1- 72	
	Line 4 is skipped.		
"WORST (HIGHEST) "	5	1- 16	A
"RELATIVE HUMIDITY = "	5	17- 36	A
IWRH	5	37- 39	13
" PERCENT"	5	40- 48	A
	Line 6 is skipped.		
"WORST (LOWEST) "	7	1- 15	A
"DISPERSION INDEX ="	7	16- 33	A
IWDINX	7	34- 37	14
" "	7	38- 40	A
KWDINX (DI adjective)	7	41- 52	A
	Line 8 is skipped.		
"WORST (HIGHEST) LOW VISIBILITY "	9	1- 31	A
"OCCURRENCE RISK INDEX ="	9	32- 54	A
IWLVRI	9	55- 57	13
" "	9	58- 60	A
KWLVRI (LVORI class description)	9	61- 88	A
"(THE BASE LINE RISK OF "	10	1- 23	A
"LOW VISIBILITY OCCURRENCE "	10	24- 49	A
"IS ABOUT 1 IN 1000)"	10	50- 68	A
	Line 11 is skipped.		

IF LSIGHT = TRUE, THEN:

Lines 12 and 13 appear as follows:

---

[1] 3I2 may be used

Continued

Variable/Text	Line(s)	Column(s)	Format
"WORST INDJVIDUAL OCCURRENCE "	12	1- 28	A
"SMOKE CONCENTRATION"	12	29- 47	A
"/VISIBILITY TABLE"	12	48- 65	A
"THE FOLLOWING TABLE IS BASED ON"	13	1- 31	A
" A CRITICAL CONTRAST RATIO = 0"	13	32- 61	A[2]
CCOCRT	13	62- 68	F7.6
", WITH HORIZONTAL CROSSPLUME"	13	69- 97	A
" VISIBILITY = "	13	98-110	A
VISCRT	13	111-120	F10.4
"MILES."	13	121-127	A

ELSE IF LSIGHT = FALSE, THEN:

Lines 12 and 13 appear as follows:

"WORST INDIVIDUAL OCCURRENCE "	12	1- 28	A
"SMOKE CONCENTRATION"	12	29- 47	A
"TABLE:"	12	48- 54	A

Line 13 is skipped.

END Line 18 block IF.

Line 14 is skipped.

IF LSIGHT = TRUE, THEN:

Lines 15-18 appear as follows:

"DOWNWIND "	15	1- 13	A
"PM CENTERLINE "	15	14- 31	A
"CO CENTERLINE "	15	32- 48	A
"CROSSPLUME "	15	49- 62	A
" CONTRAST"	15	63- 72	A
" DOWNWIND"	15	73- 84	A
"DISTANCE "	16	1- 13	A
"CONCENTRATION "	16	14- 31	A
"CONCENTRATION "	16	32- 48	A

[2] Can use F8.6 for col. 61-68

Variable/Text	Line(s)	Column(s)	Format
“VISIBILITY "	16	49- 62	A
" RATIO AT”	16	63- 72	A
" DISTANCE”	16	73- 84	A
“FROM FIRE "	17	1- 13	A
"(INCL. BKGPM) "	17	14- 31	A
"(INCL. BKGCO) "	17	32- 48	A
“FOR LOW RH "	17	49- 62	A
VISCRT	17	63- 72	F10.4
" FROM FIRE”	17	73- 85	A
" (KM) "	18	1- 13	A
" (UG M^{-3}) "	18	14- 31	A
" (PPM) "	18	32- 48	A
" (MILES) "	18	49- 62	A
" MILES "	18	63- 72	A
" (KM)"	18	73- 82	A

<u>ELSE IF</u> LSIGHT = FALSE, THEN:

Lines 15-18 appear as follows:

Variable/Text	Line(s)	Column(s)	Format
“DOWNWIND "	15	1- 13	A
“PM CENTERLINE "	15	14- 31	A
“CO CENTERLINE”	15	32- 44	A
" DOWNWIND”	15	45- 56	A
“DISTANCE "	16	1- 13	A
“CONCENTRATION "	16	14- 31	A
“CONCENTRATION”	16	32- 44	A
" DISTANCE”	16	45- 56	A
“FROM FIRE "	17	1- 13	A
“(INCL. BKGPM) "	17	14- 31	A
“(INCL. BKGCO)”	17	32- 44	A
" FROM FIRE”	17	45- 57	A
" (KM) "	18	1- 13	A
" (UG M^{-3})	18	14- 31	A
" (PPM) "	18	32- 44	A
" (KM)"	18	45- 54	A

<u>END</u> Lines 15 to 18 block <u>IF</u>.

Line 19 is skipped.

Variable/Text	Line(s)	Column(s)	Format
IF LSIGHT = TRUE, **THEN:**			
	Lines 20-50 appear as follows:		
DSKM(J) (downwind distance)	20-50	1- 8	F8.3
WCHIPM(J) (worst part. conc.)	20-50	9- 26	F18.3
WCHICO(J) (worst CO conc.)	20-50	27- 44	F18.6
WVIS(J) (sightline visibility)	20-50	45- 58	F14.5
Blank	20-50	59	1x
Blank (or asterisk, IF RH GE.70%)	20-50	60	A
WCCO(J) (worst contrast ratio)	20-50	61- 72	F12.6
Blank	20-50	73	1x
Blank (or asterisk, IF RH.GE.70%)	20-50	74	A
Blanks	20-50	75- 76	X
DSKM(J) (repeated for readabil.)	20-50	77- 84	F8.3
ELSE IF LSIGHT = FALSE, **THEN:**			
	Lines 20-50 appear as follows:		
DSKM(K) (downwind distance)	20-50	1- 8	F8.3
WCHIPM(J) (worst part. conc.)	20-50	9- 26	F18.3
WCHICO(J) (worst CO conc.)	20-50	27- 44	F18.6
Blanks	20-50	45- 48	4x
DSKM(J) (repeated for readabil.)	20-50	49- 56	F8.3
END Lines 20 to 50 block **IF**.			
IF LSIGHT = TRUE, THEN:			
	Line 5 1 appears as follows:		
"BACKGROUND"	51	1- 10	A
WCHIPM(21) (worst bkg. PM conc.)	51	11- 26	F16.3
WCHICO(21) (worst bkg. CO conc.)	51	27- 44	F18.6
WVIS(21) (worst bkg. visibility)	51	45- 58	F14.5
Blank	51	59	X
Blank (or asterisk, IF RH.GE.70%)	51	60	A
WCCO(21) (worst contrast ratio)	51	61- 72	F12.6
Blank	51	73	1x
Blank (or asterisk, IF RH.GE 70%)	51	74	A

Variable/Text	Line(s)	Column(s)	Format
Blanks	51	75- 76	2x
"BACKGROUND" (repeated)	51	77- 86	A

ELSE IF LSIGHT = FALSE, THEN:

Line 51 appears as follows:

"BACKGROUND"	51	1- 10	A
WCHIPM(21) (worst bkg. PM conc.)	51	11- 26	F16.3
WCHICO(21) (worst bkg. CO conc.)	51	27- 44	F18.6
Blanks	51	45- 48	4X
"BACKGROUND" (repeated)	51	49- 58	A

END Line 5 1 block IF.

Line 52 is skipped.

IF LSIGHT = TRUE, AND RELATIVE HUMIDITY EQUALS OR EXCEEDS 70 PERCENT, THEN:

Line 53 appears as follows:

"* RELATIVE HUMIDITY "	53	1- 24	A
"EQUALS OR EXCEEDS 70 PERCENT,"	53	25- 54	A
" ACTUAL VISIBILITIES AND "	53	55- 79	A
"CONTRAST RATIOS MAY BE MUCH "	53	80-101	A
"LESS THAN ESTIMATED."	53	102-121	A

ELSE IF LSIGHT = FALSE, OR RELATIVE HUMIDITY IS LESS THAN 70 PERCENT, THEN:

Line 53 is skipped.

END Line 53 block IF.
IF LSIGHT = TRUE, THEN:

Line 54 appears as follows:

Blank (or asterisk IF RH.GE.70%)	54	1	A
Blanks	54	2- 10	A
"DRY WEATHER CROSSPLUME "	54	11- 33	A
"VISIBILITIES ARE "	54	34- 50	A

Variable/Text	Line(s)	Column(s)	Format
"AT LEAST", OR "LESS THAN "[3]	54	51- 60	A
VISCRT	54	61- 70	F10.4
" MILES, AT AND BEYOND "	54	71- 92	A
DSKM(JVSOK), OR "100.000"[4]	54	93- 99	F7.3[5]
" KM FROM THE FIRE."	54	100-117	A
ELSE IF LSIGHT = FALSE, THEN:			
	Line 54 is skipped.		
END Line 54 block IF.			
	Line 55 is skipped.		
	Line 56 is skipped.		
	Line 57 is skipped.		
"LRUNOK = "	58	1- 9	A
LRUNOK (LOGICAL, T vs. F, variable)	58	10	L1
	Line 59 is skipped.		
"END OF VSMOKE RUN."	60	1- 18	A

[3] Line 54: First altemative applies if the crossplume visibility 100.000 km downwind of the fire (i.e., the value of VXPLMI at line 50, cols. 45-58) is at least VISCRT; otherwise, the second alternative applies.

[4] Line 54: DSKM(JVSOK) is the shortest downwind distance for which estimated visibility is at least VISCRT at this and all longer distances analyzed in the program.

[5] OK for both.

List of Figures

Table 1—Stability class dependent constants for determining σ_Y in equation 23

Stability class	Value of A	Value of B
	(degrees)	(degrees)
1 - extremely unstable	24.1670	-2.53340
2 - moderately unstable	18.3330	-1.80960
3 - slightly unstable	12.5000	-1.08570
4d - near neutral - day	8.3333	-0.72382
4n - near neutral - night	8.3333	-0.72382
5 - slightly stable	6.2500	-0.54287
6 - moderately stable	4.1667	-0.36191
7 - extremely stable	4.1667	-0.36191

Table 2—Approximate horizontal spread angles in degrees as a function of downwind distance and stability class

Downwind distance	Stability class					
	1	2	3	4(d/n)[a]	5	6 or 7
(km)						
0.100	30.000	22.500	15.000	10.000	7.500	5.000
1.000	24.167	18.333	12.500	8.333	6.250	4.167
10.000	18.333	14.167	10.000	6.667	5.000	3.333
100.000	12.500	10.000	7.500	5.000	3.750	2.500

[a] Horizontal spread angles are the same for stability class 4—day or night.

Table 3—Stability class and downwind distance dependent constants for determining σ_z in equation 24

Stability class	Downwind distance (km)	Value of C	Value of D
1	< 0.1	122.8	0.9447
1	0.1 - 0.15	158.08	1.0542
1	0.15 - 0.2	170.22	1.0932
1	0.2 - 0.25	179.52	1.1262
1	0.25 - 0.3	217.41	1.2644
1	0.3 - 0.4	258.89	1.4094
1	0.4 - 0.5	346.75	1.7283
1	> 0.5	453.85	2.1166
2	< 0.2	90.673	0.93198
2	0.2 - 0.4	98.483	0.98332
2	> 0.4	109.30	1.0971
3	all	61.141	0.91465
4 day	< 0.3	34.459	0.86974
4 day	> 0.3	32.354	0.81738
4 night	< 0.3	34.459	0.86974
4 night	0.3 - 1	32.093	0.81066
4 night	1 - 3	32.093	0.64403
4 night	3 - 10	33.504	0.60486
4 night	10 - 30	36.650	0.56589
4 night	> 30	44.053	0.51179
5	< 0.1	24.26	0.8366
5	0.1 - 0.3	23.331	0.81956
5	0.3 - 1	21.628	0.75660
5	1 - 2	21.628	0.63077
5	2 - 4	22.534	0.57514
5	4 - 10	24.703	0.50527
5	10 - 20	26.970	0.46713
5	20 - 40	35.420	0.37615
5	> 40	47.618	0.29592
6 or 7	< 0.2	15.209	0.81558
6 or 7	0.2 - 0.7	14.457	0.78407

Continued

Table 3—Stability class and downwind distance dependent constants for determining σ_z in equation 24 (continued)

Stability class	Downwind distance (km)	Value of C	Value of D
6 or 7	0.7 - 1	13.953	0.68465
6 or 7	1 - 2	13.953	0.63227
6 or 7	2 - 3	14.823	0.54503
6 or 7	3 - 7	16.187	0.46490
6 or 7	7 - 15	17.836	0.41507
6 or 7	15 - 30	22.65 1	0.32681
6 or 7	30 - 60	27.074	0.27436
6 or 7	> 60	34.219	0.21716

Table 4-Dispersion Index Interpretation, adapted from Lavdas (1986)

DI value	Interpretation	Conditions
> 100	Very Good	May indirectly indicate hazardous burning conditions; check fire weather
61 - 100	Good	"Good burning weather" conditions (Southern Forest Fire Laboratory Personnel 1976) are typically in this range
41 - 60	Fair to Good	Climatological afternoon values in most inland forested areas of the United States are in this range
21 - 40	Fair	Stagnation may be indicated if accompanied by persistent low windspeeds
13 - 20	Fair to Poor	Stagnation if persistent, but better than average for a night value
7 - 12	Poor	Stagnant at day, but near or above average at night
1 - 6	Very Poor	Very frequent at night, occurs on a majority of nights in many locations

Table S-Low Visibility Occurrence Risk Index-as a function of relative humidity and Dispersion Index based on the proportion of accidents with fog and/or smoke, as reported by the Florida Highway Patrol, 1979-1981, (Lavdas and Hauck 1991)

Relative Humidity	Dispersion Index												
	1	2	3-4	5-6	7-8	9-10	11-12	13-16	17-20	21-25	26-30	31-40	>40
<55	2	2	2	2	2	2	2	2	2	2	2	1	1
55-59	3	3	3	3	3	2	2	2	2	2	2	1	1
60-64	3	3	3	3	3	3	2	2	2	2	2	1	1
65-69	4	3	3	3	3	3	3	3	3	3	3	3	1
70-74	4	3	3	3	3	3	3	3	3	3	3	3	3
75-79	4	4	4	4	4	4	4	4	3	3	3	3	3
80-82	6	5	5	4	4	4	4	4	3	3	3	3	3
83-85	6	5	5	5	4	4	4	4	4	4	4	4	4
86-88	6	6	6	5	5	5	5	4	4	4	4	4	4
89-91	7	7	6	6	5	5	5	5	4	4	4	4	4
92-94	8	7	6	6	6	6	5	5	5	5	4	4	4
95-97	9	8	8	7	6	6	6	5	5	5	4	4	4
>97	10	10	9	9	8	8	7	5	5	5	4	4	4

Key to lo-point scale:

1 - Lowest proportion of accidents with fog and/or smoke reported (130 out of 127,604 accidents, or just over 1 out of 1,000 accidents in this category)
2 - Physical or statistical reasons for not including as a part of category 1, but proportion of accidents with fog and/or smoke not significantly higher
3 - Higher proportion of accidents than category 1, by about 30 to 50 percent, marginally significant
4 - Significantly higher proportion than category 1, by about a factor of 2
5 - Significantly higher proportion than category 1, by a factor of 3 to 10
6 - Significantly higher proportion than category 1, by a factor of 10 to 20
7 - Significantly higher proportion than category 1, by a factor of 20 to 40
8 - Significantly higher proportion than category 1, by a factor of 40 to 75
9 - Significantly higher proportion than category 1, by a factor of 75 to 125
10 - Significantly higher proportion than category 1, by about a factor of 150

Note: The overall number of accidents with fog, smoke, or both reported is 3,235 out of a total of 433,649 accident reports analyzed. Of these, 604 included smoke, 2,972 included fog, and 341 included both.

Table 6-Index of downwind distances by line number for concentration (/visibility) tables iu output Sections 2 and 3

Downwind distance from fire (km)	Period/page line number for Section 2	Line number for Section 3
0.100	26	20
0.126	27	21
0.158	28	22
0.200	29	23
0.25 1	30	24
0.316	31	25
0.398	32	26
0.501	33	27
0.63 1	34	28
0.794	35	29
1.000	36	30
1.259	37	31
1.585	38	32
1.995	39	33
2.512	40	34
3.162	41	35
3.981	42	36
5.012	43	37
6.310	44	38
7.943	45	39
10.000	46	40
12.589	47	41
15.849	48	42
19.953	49	43
25.119	50	44
31.623	51	45
39.811	52	46
50.119	53	47
63.096	54	48
79.433	55	49
100.000	56	50
BACKGROUND VALUES	57	51

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(pages in boldface contain primary definitions or discussions for the given entry)

Lavdas, Leonidas G. 1996. Program VSMOKE-Users Manual. Gen. Tech. Rep. **SRS-6.** Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 147 p.

This is a users manual for VSMOKE, a computer program for predicting the smoke and dry weather visibility impact of a single prescribed fire at several downwind locations. VSMOKE is a FORTRAN 77 program that depends on the input in tile **VSMOKE.IPT** to generate output in file VSMOKE.OUT. VSMOKE is based on steady-state Gaussian plume modeling principles compatible with those used by the U.S. Environmental Protection Agency. VSMOKE is uniquely tailored as a plume model for a low to moderate intensity ground fire as an emissions source.

Keywords: Computer models, prescribed fire, smoke, visibility, VSMOKE.